

dark matter

Milena Crnogorčević

Postdoctoral Fellow at the Oskar Klein Centre
→ GRAPPA, University of Amsterdam [Fall 2026]

International School of Cosmic Ray Astrophysics 2026
Erice



dark matter

1

Dark Matter Introduction

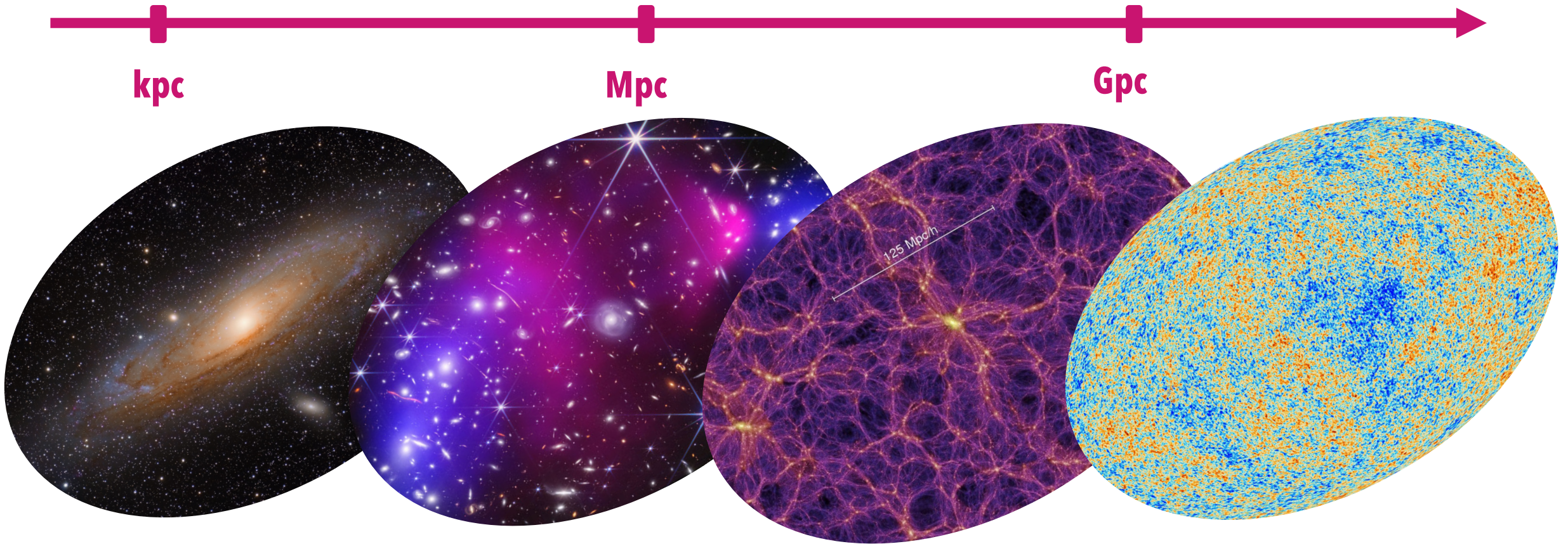
2

Dark Matter Candidates and Detection
Strategies

3

Indirect Detection

Take-home message: dark matter acting across the scales



A single non-baryonic dark-matter component consistently explains observations across these scales

dark matter

1

Dark Matter Introduction

2

**Dark Matter Candidates and
Detection Techniques**

3

Indirect Detection

What properties must the dark matter have?
What candidates satisfy these requirements?
How can we detect them?



Join at
slido.com
#3398 781

Gravitational Anomalies (The Dark Matter Problem)

- Low-mass dark matter particles (e.g., axions)
- High-mass dark matter particles (e.g., WIMPs)
- A modification to classical gravity on galaxy scales (e.g., MOND)
- Primordial black holes
- A hybrid of the above
- Effects of quantum gravity
- Other
- No opinion

Gravitational Anomalies (The Dark Matter Problem)

The observed rotation rates of galaxies are faster than expected, given the gravitational pull of the light-emitting matter contained in the galaxies. These rotation rates and related observations (e.g., clusters of galaxies, baryonic acoustic oscillation, and cosmic microwave background anisotropies) have led to proposals for “new physics” either in the form of dark matter or of modifications to the laws of gravity. In your opinion what is the most likely candidate for explaining these gravitational anomalies?

Low-mass dark matter particles (e.g., axions)	17%
---	-----

High-mass dark matter particles (e.g., WIMPs)	10%
---	-----

A modification to classical gravity on galaxy scales (e.g., MOND)	12%
---	-----

Primordial black holes	5%
------------------------	----

A hybrid of the above	21%
-----------------------	-----

Effects of quantum gravity	10%
----------------------------	-----

Other	10%
-------	-----

No opinion	15%
------------	-----

Properties of dark matter (observations)

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants
dark*/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent

*misnomer: dark things absorb. It's *transparent*

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants
dark/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent
long-lived	DM still exists; CMB/indirect decay searches	$\tau \gtrsim t_U \sim 4 \times 10^{17} \text{ s}$ visible decays $\gtrsim 10^{26} \text{ s}$

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants
dark/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent
long-lived	DM still exists; CMB/indirect decay searches	$\tau \gtrsim t_U \sim 4 \times 10^{17} \text{ s}$ visible decays $\gtrsim 10^{26} \text{ s}$
weakly self-interacting	merging clusters, halo dynamics	$\sigma/m \lesssim \mathcal{O}(1) \text{ cm}^2 \text{ g}^{-1}$ @ cluster velocities

Clowe+ astro-ph/0608407; Randall+ 0704.0261; Sagunski+ 2006.12515; Tulin & Yu 1705.02358

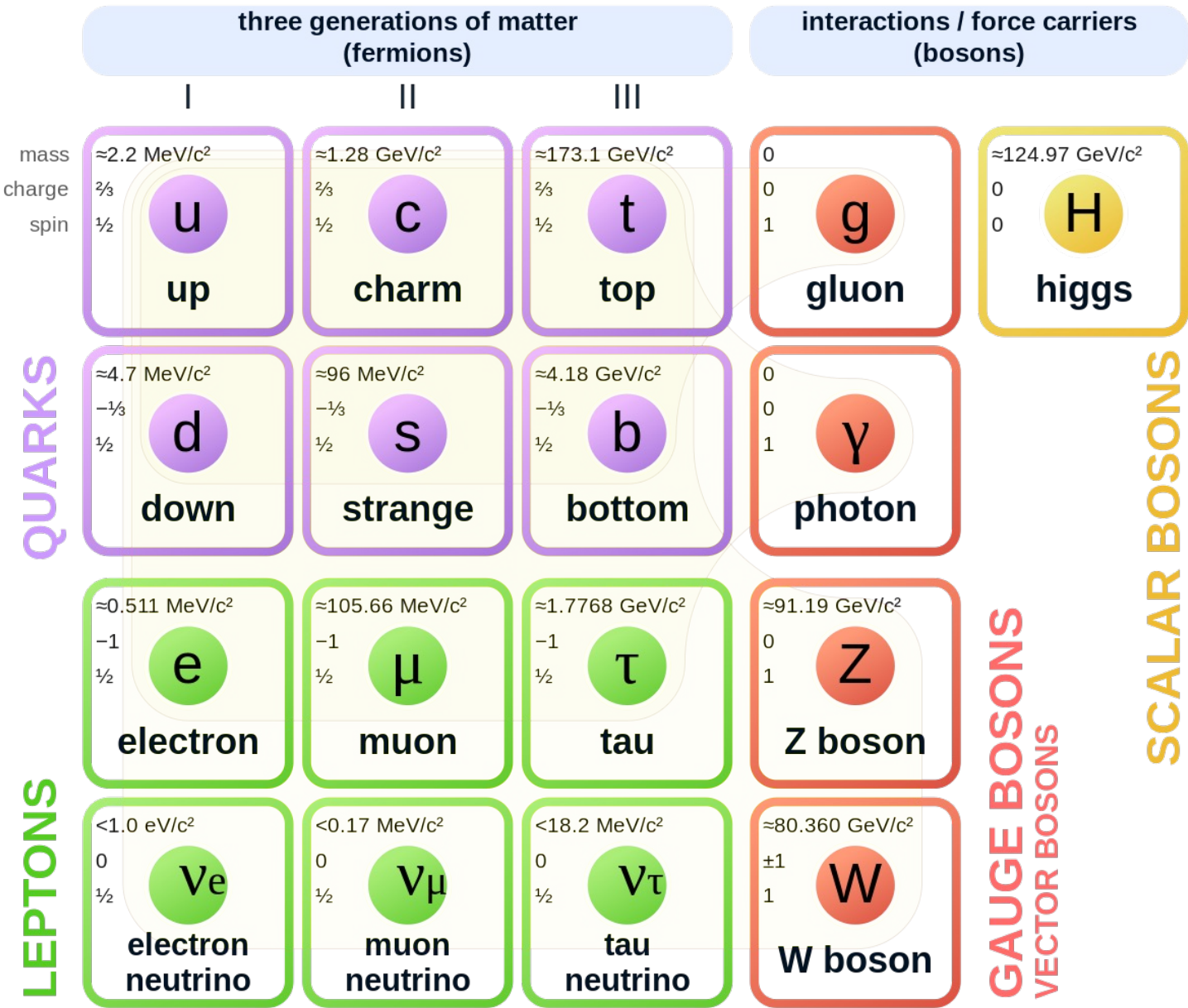
Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants
dark/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent
long-lived	DM still exists; CMB/indirect decay searches	$\tau \gtrsim t_U \sim 4 \times 10^{17} \text{ s}$ visible decays $\gtrsim 10^{26} \text{ s}$
weakly self-interacting*	merging clusters, halo dynamics	$\sigma/m \lesssim \mathcal{O}(1) \text{ cm}^2 \text{ g}^{-1}$ @ cluster velocities
dissipationless**	extended halos rather than a cooled dark disk	no universal single number (halo axis ratio $\sim 0.7\text{--}1$)

*bounds elastic scattering. **bounds inelastic/dissipative processes.

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_b = 5.36 \rightarrow$ not ordinary baryonic gas/stars/compact remnants
dark/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent
long-lived	DM still exists; CMB/indirect decay searches	$\tau \gtrsim t_U \sim 4 \times 10^{17} \text{ s}$ visible decays $\gtrsim 10^{26} \text{ s}$
weakly self-interacting	merging clusters, halo dynamics	$\sigma/m \lesssim \mathcal{O}(1) \text{ cm}^2 \text{ g}^{-1}$ @ cluster velocities
dissipationless	extended halos rather than a cooled dark disk	no universal single number (halo axis ratio $\sim 0.7\text{--}1$)
Viel+ 1306.2314; Iršič+ 1702.01764; Tremaine & Gunn (1979); Alvey+ 2010.03572; Zimmermann+ 2405.20374		
cold/small primordial velocity dispersion	Lyman- α forest & small-scale structure; CMB	perturbation size $< \lambda_{fs} \sim v(t_{eq})/H(t_{eq})$ doesn't survive (est. $\sim 0.17(\text{keV}/m_{DM}) \text{ Mpc}$)

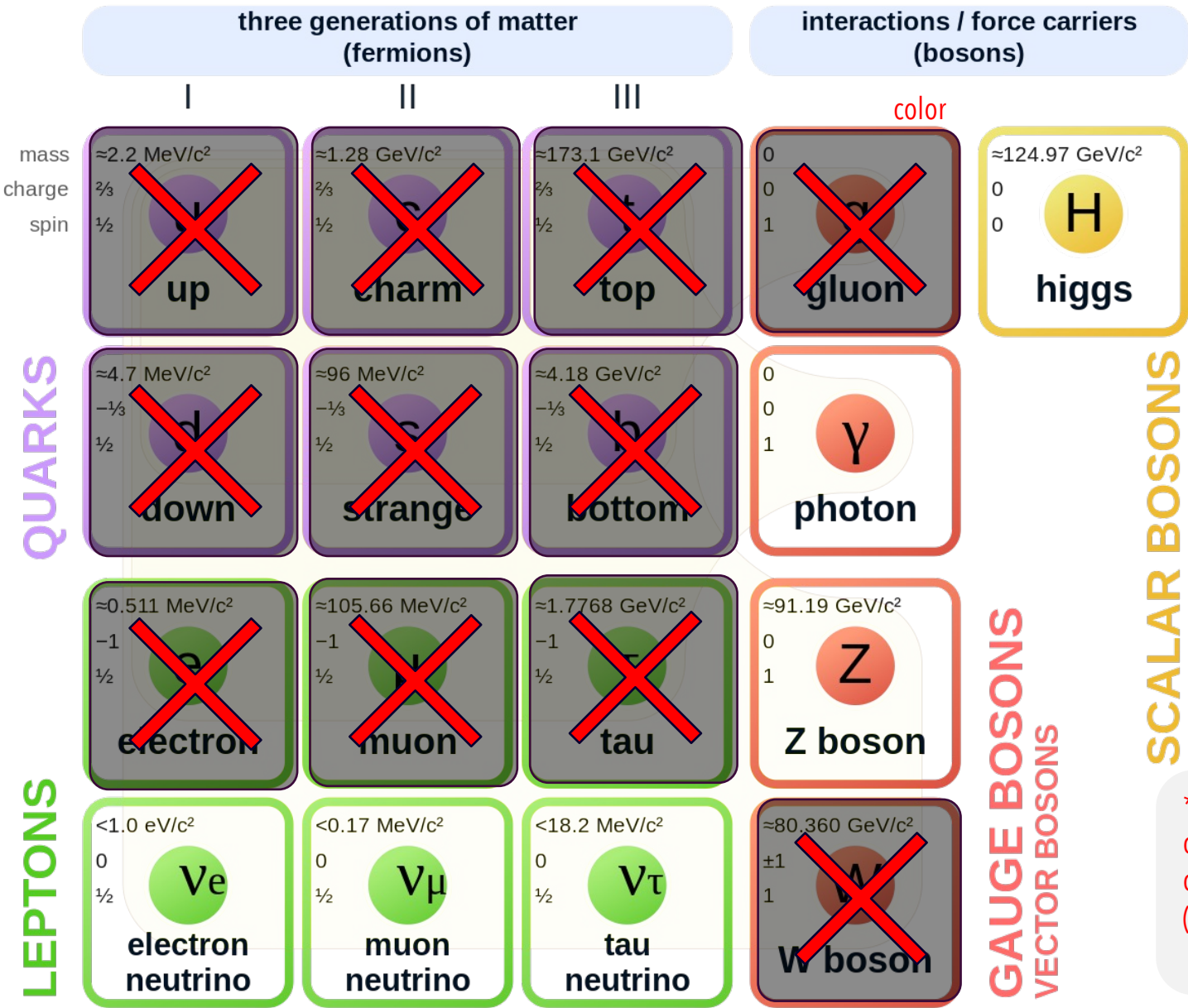
Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles



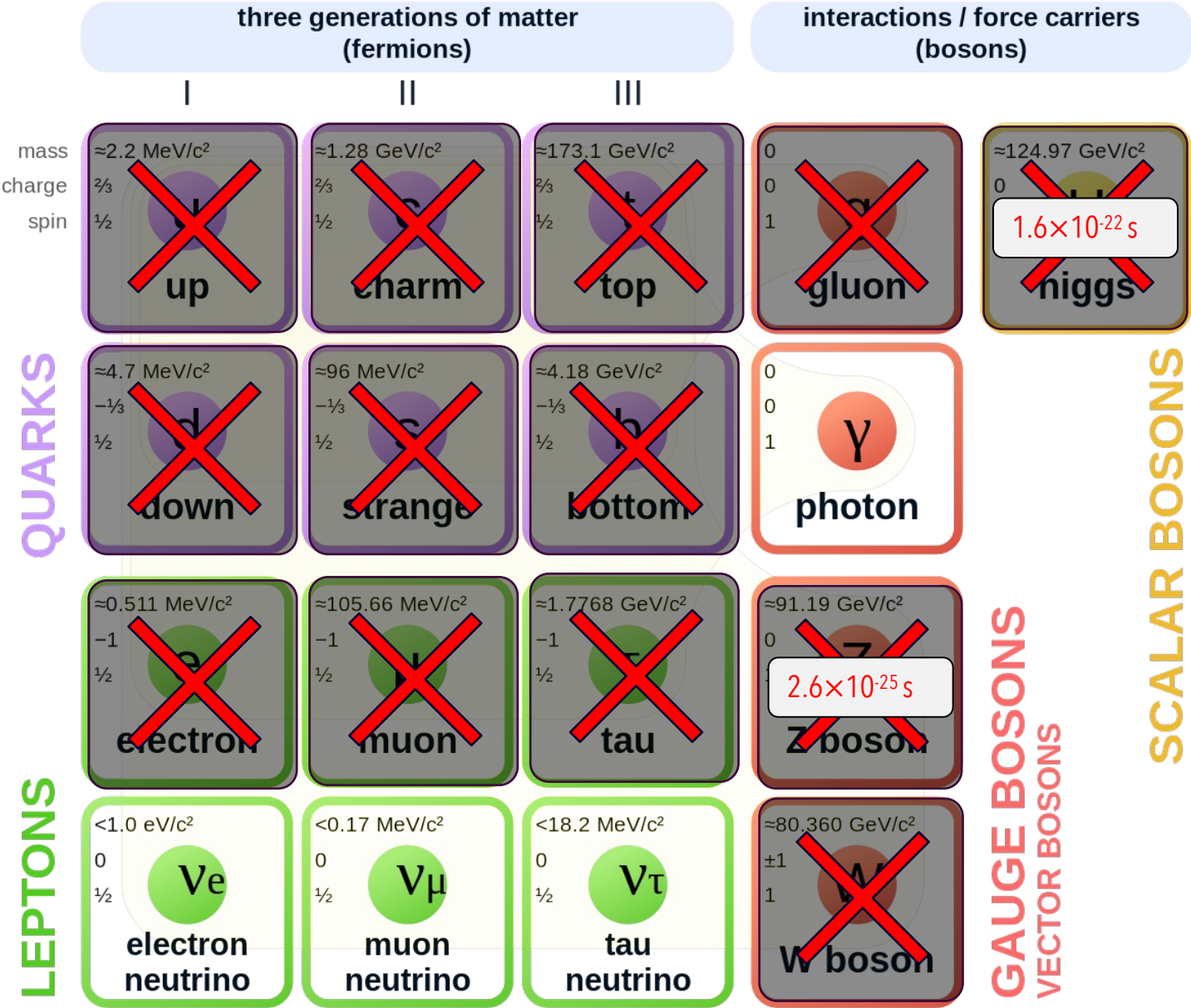
Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled*
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles



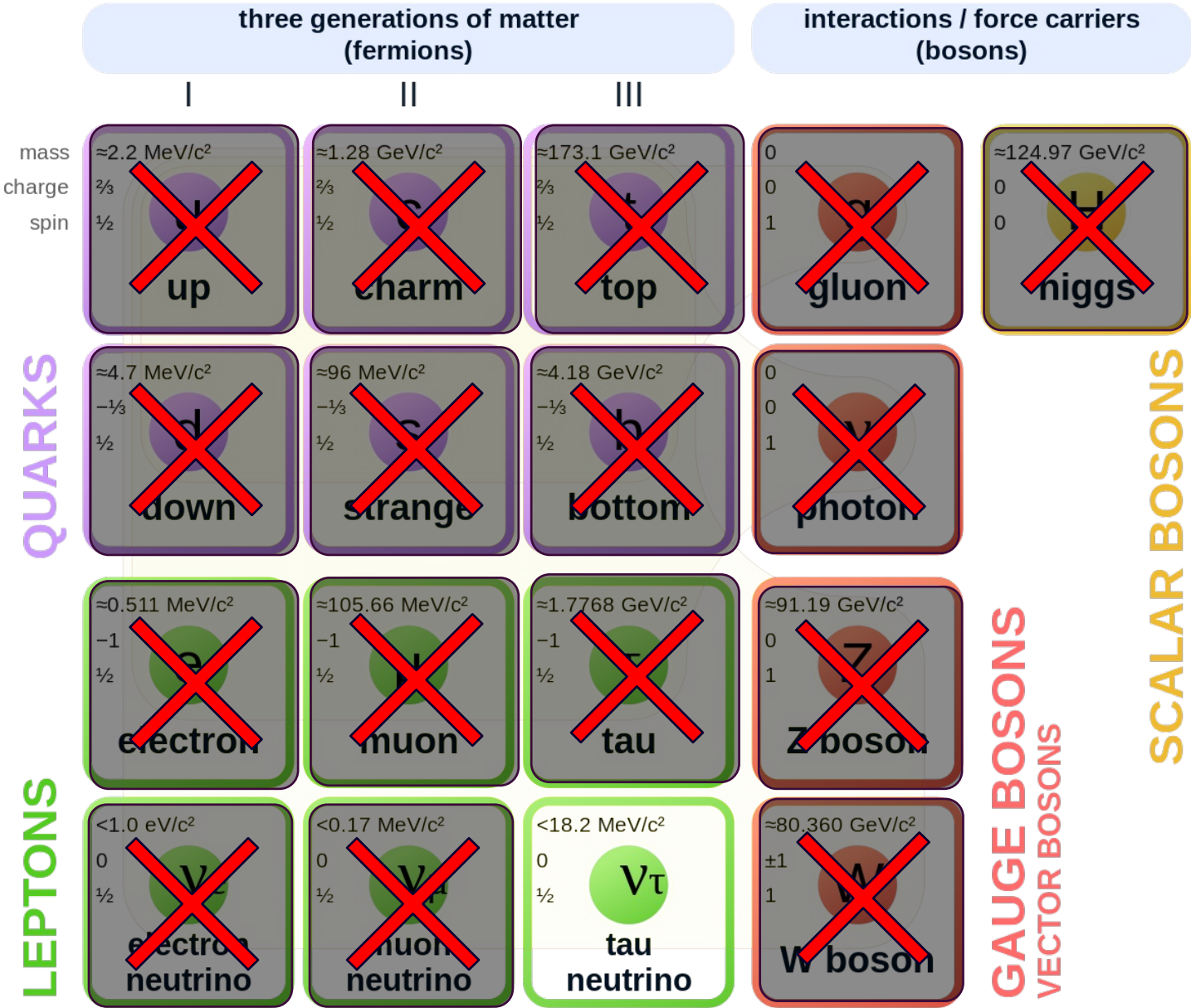
Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles



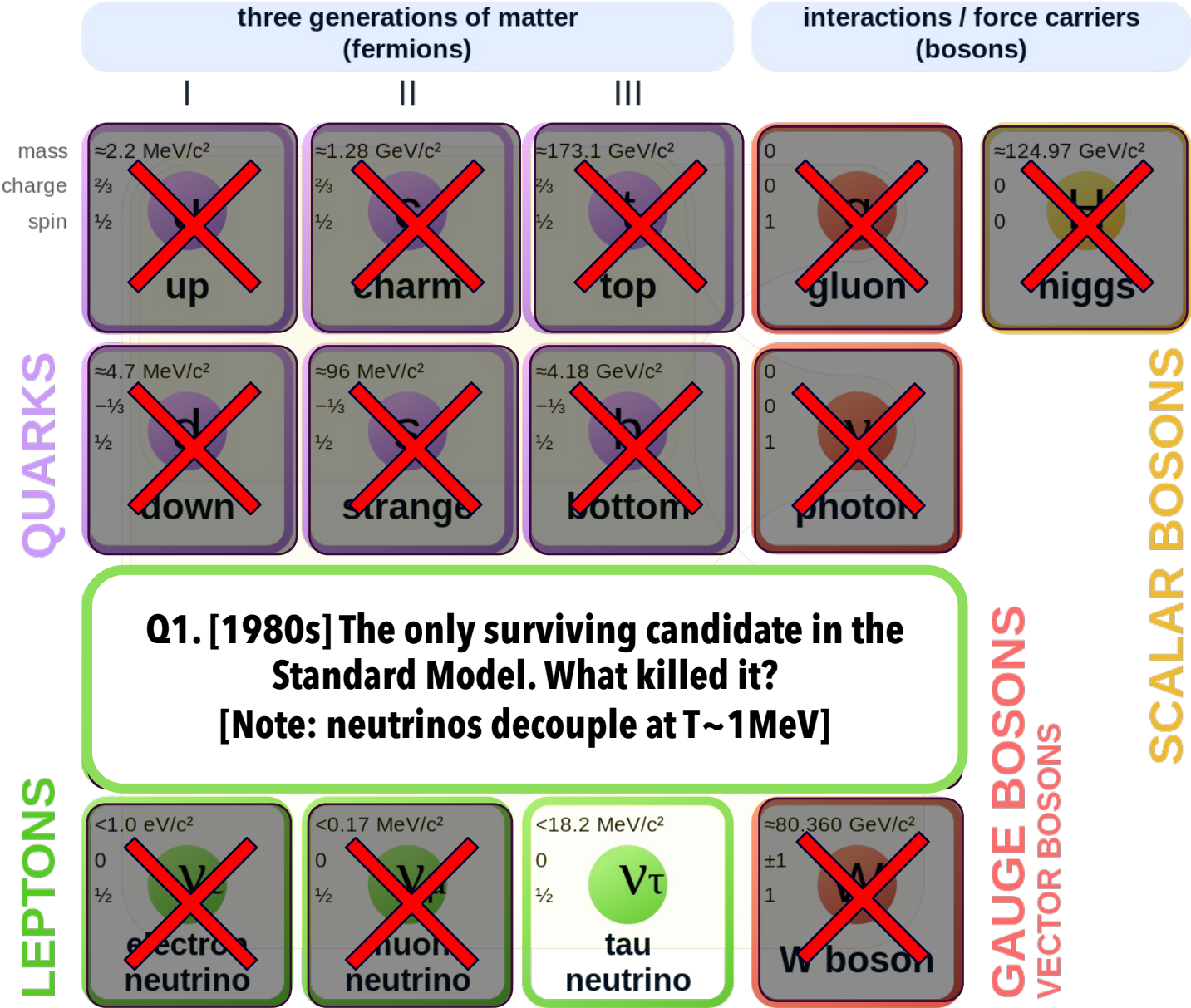
Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles



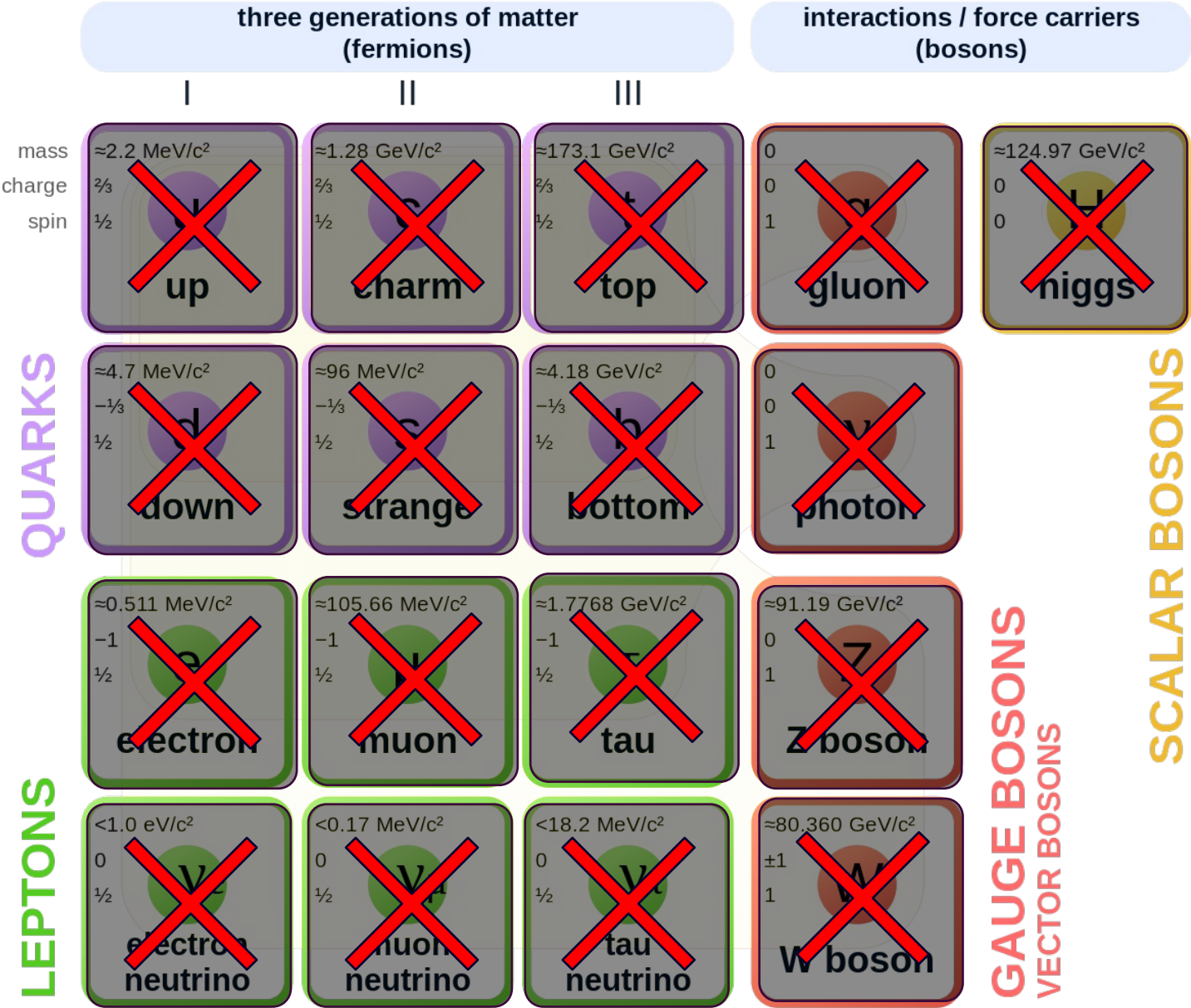
Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles



Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

Standard Model of Elementary Particles

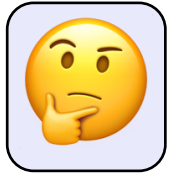


Requirement
gravitates & clusters
non-baryonic
dark/weakly SM-coupled
long-lived
weakly self-interacting
dissipationless
cold/small primordial velocity dispersion

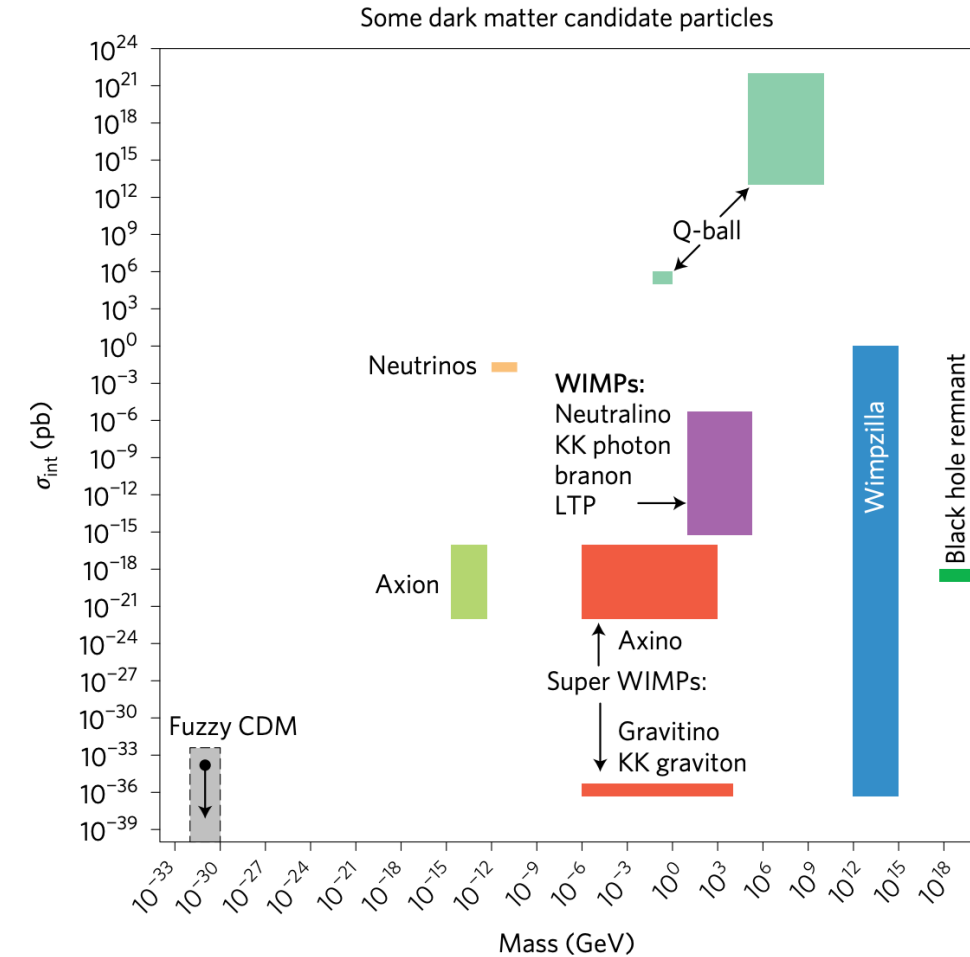


Observations give us requirements, not a unique particle.

Observations give us requirements, not a unique particle.



→ Many very different candidates can satisfy the basic DM requirements and span enormous ranges in mass and interaction strength.



Conrad & Reimer, Nature Physics 13 (2017) 224–231

Observations give us requirements, not a unique particle.



→ Many very different candidates can satisfy the basic DM requirements and span enormous ranges in mass and interaction strength.

Theory

→ We need additional input from theory:

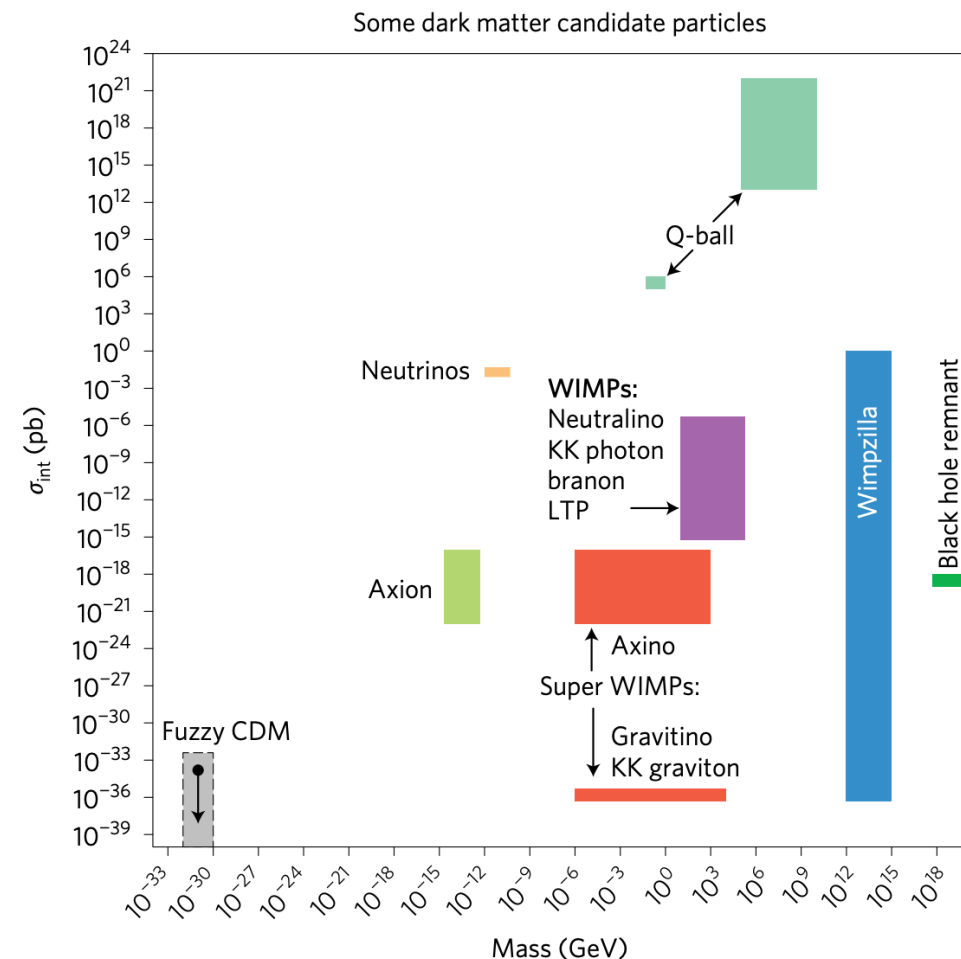
What is its mass?

What does it couple to?

How was it produced?

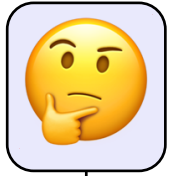
→ **the dark matter zoo**

Candidate



Conrad & Reimer, Nature Physics 13 (2017) 224–231

Observations give us requirements, not a unique particle.



→ Many very different candidates can satisfy the basic DM requirements and span enormous ranges in mass and interaction strength.

Theory

→ We need additional input from theory:
What is its mass?
What does it couple to?
How was it produced?

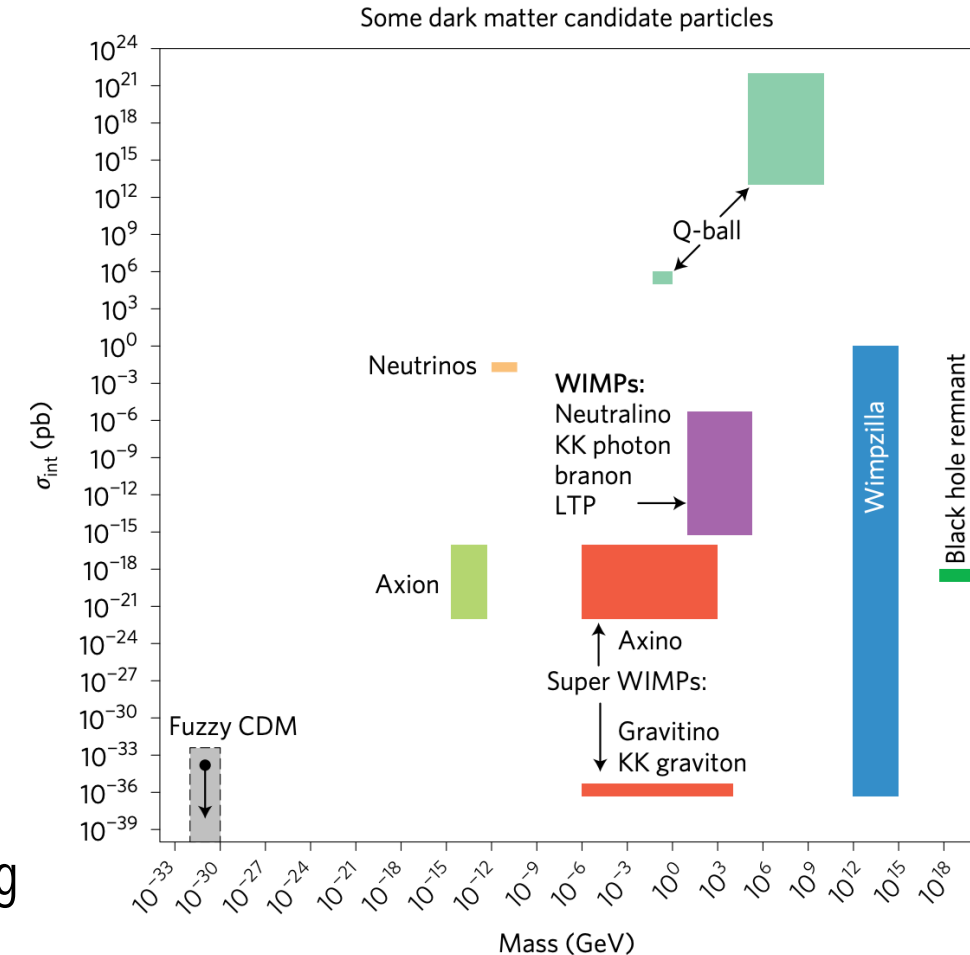
Candidate

→ **the dark matter zoo**

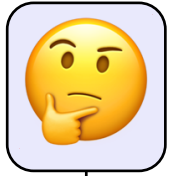
Signature
&
Search
Strategy

→ Once a theoretical framework is specified, we can ask how that candidate could reveal itself and design the corresponding search.

→ Identification strategies are therefore **necessarily model-dependent** – to varying degrees



Observations give us requirements, not a



→ Many very different candidates can satisfy the b requirements and span enormous ranges in mass and interaction strength.

Theory

→ We need additional input from theory:
What is its mass?
What does it couple to?
How was it produced?

Candidate

→ **the dark matter zoo**

Signature
&
Search
Strategy

→ Once a theoretical framework is specified, we can say that candidate could reveal itself and design the corresponding search.

→ Identification strategies are therefore **necessarily dependent** – to varying degrees

Dark Matter Candidates: A Ten-Point Test

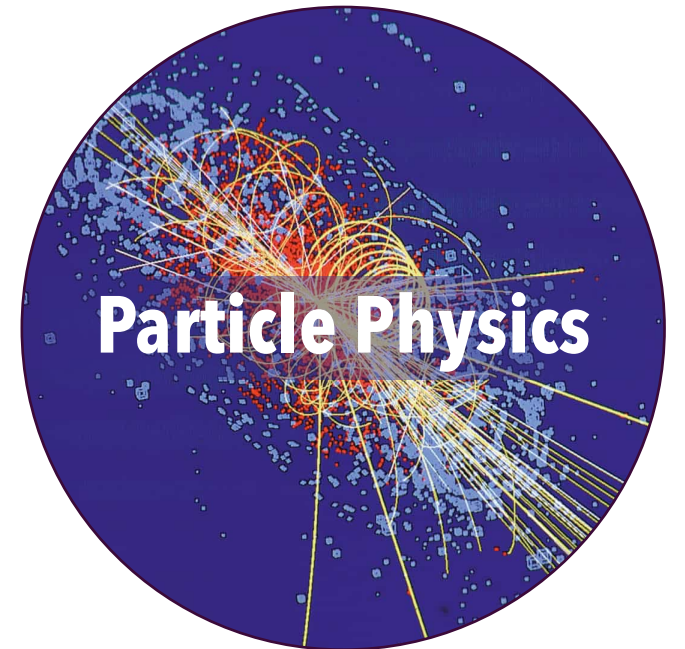
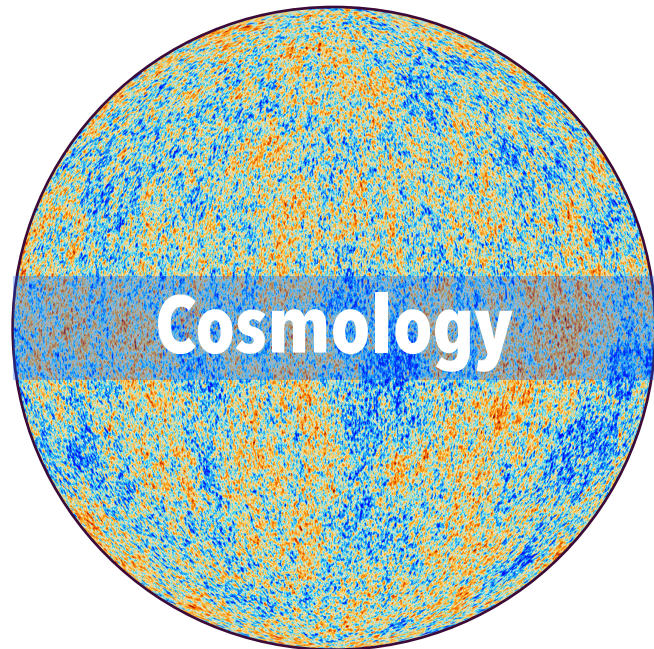
Marco Taoso^{1,2}, Gianfranco Bertone², and Antonio Masiero¹

¹ INFN, Sezione di Padova, via Marzolo 8, Padova, 35131, Italy and

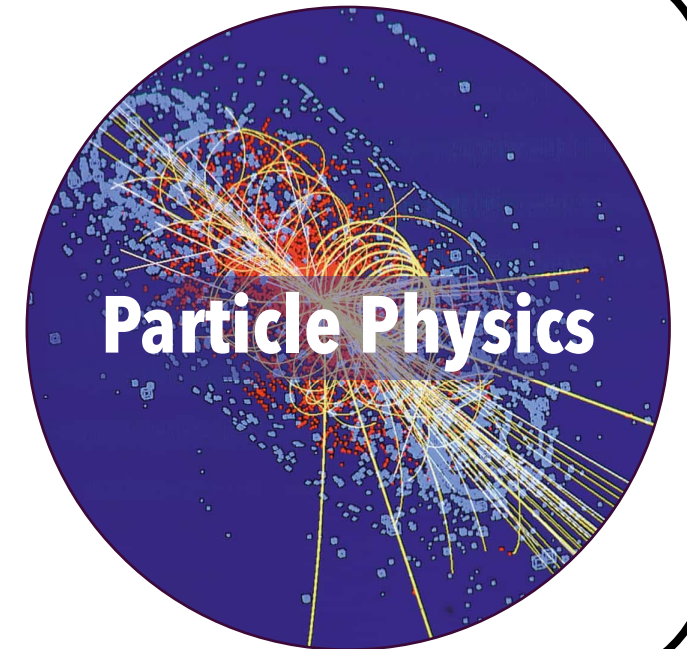
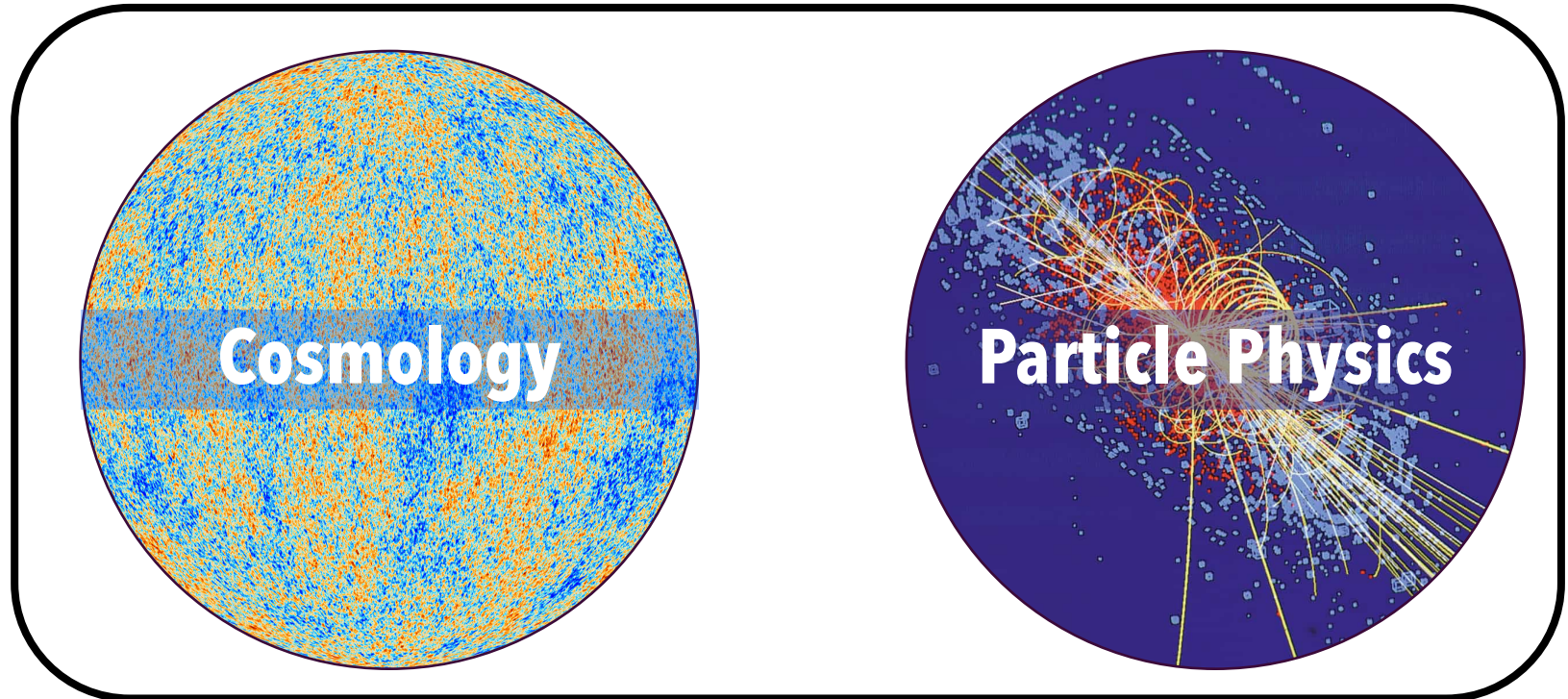
² Institut d'Astrophysique de Paris, UMR 7095-CNRS,
Université Pierre et Marie Curie, 98 bis Boulevard Arago 75014, Paris, France

1. Does it match the appropriate relic density?
2. Is it cold?
3. Is it neutral?
4. Is it consistent with BBN?
5. Does it leave stellar evolution unchanged?
6. Is it compatible with constraints on self-interactions?
7. Is it consistent with direct DM searches?
8. Is it compatible with gamma-ray constraints?
9. Is it compatible with other astrophysical bounds?
10. Can it be probed experimentally?

dark matter



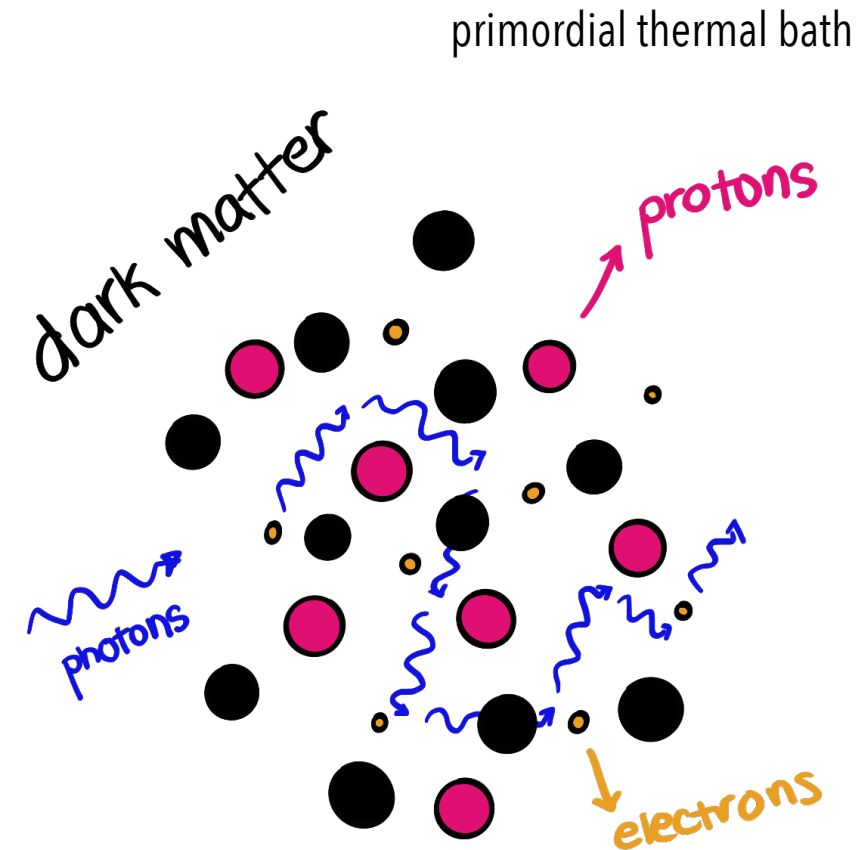
dark matter



Particle cosmology: thermal freeze-out

- Possibility (not a requirement): dark matter was just another species in the primordial thermal bath
- Suppose dark matter has some weak non-gravitational coupling to the Standard Model

$$\chi + \chi \rightleftharpoons \text{SM} + \text{SM}$$

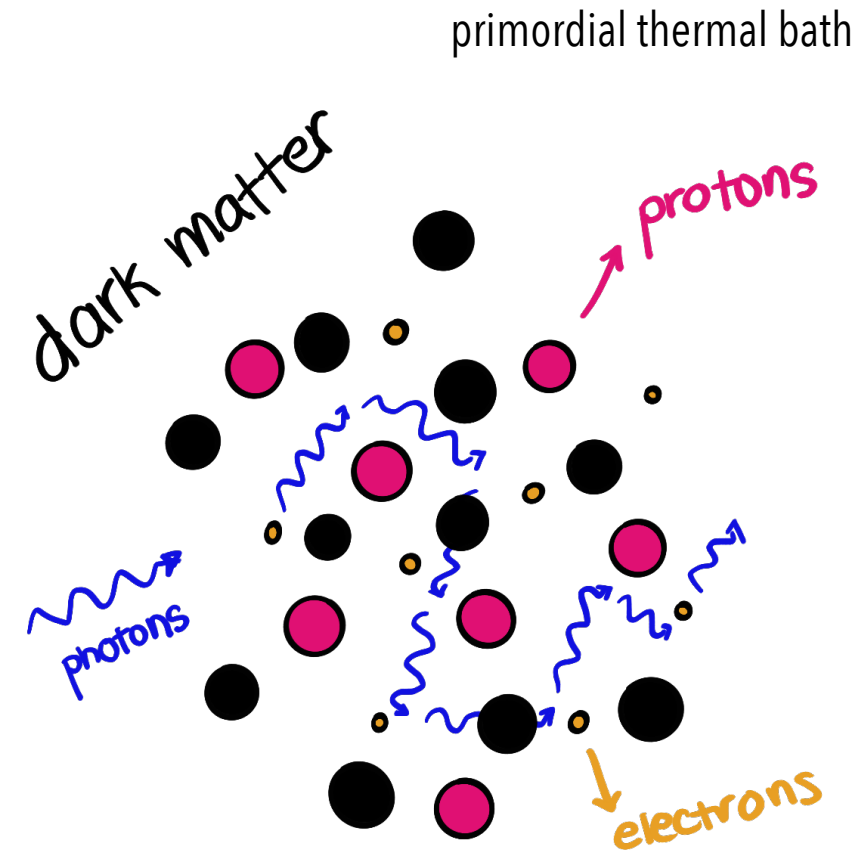


Particle cosmology: thermal freeze-out

- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

$$\dot{n}_\chi + \boxed{3Hn_\chi} = - \overset{\text{DM annihilation}}{\langle \sigma_{\chi\bar{\chi}} v \rangle_{\text{eq}}} \left[\boxed{n_\chi^2} - \underset{\text{DM production}}{n_{\chi,\text{eq}}^2} \right]$$

dilution due to expansion
DM production



Particle cosmology: thermal freeze-out

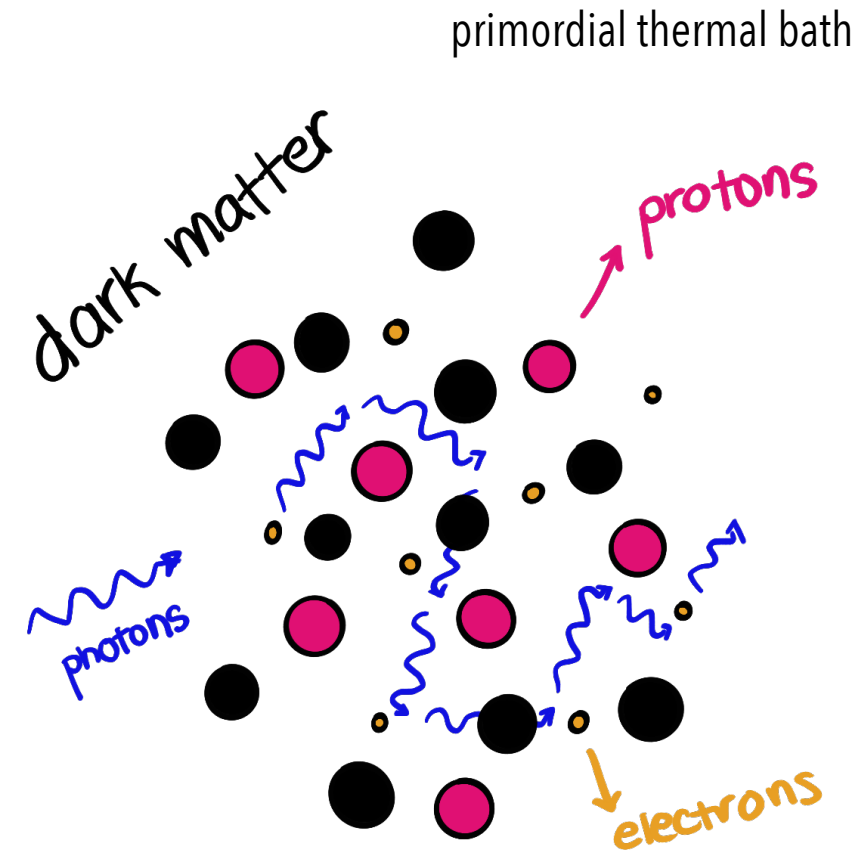
- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

$$\dot{n}_\chi + \boxed{3Hn_\chi} = - \langle \sigma_{\chi\bar{\chi}} v \rangle_{\text{eq}} \left[\boxed{n_\chi^2} - \boxed{n_{\chi,\text{eq}}^2} \right]$$

dilution due to expansion
DM annihilation
DM production

- Equilibrium number densities:

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \text{ relativistic} \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \text{ non-relativistic} \end{cases}$$



Particle cosmology: thermal freeze-out

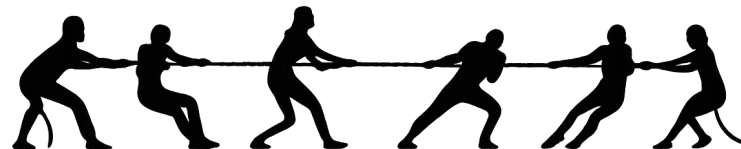
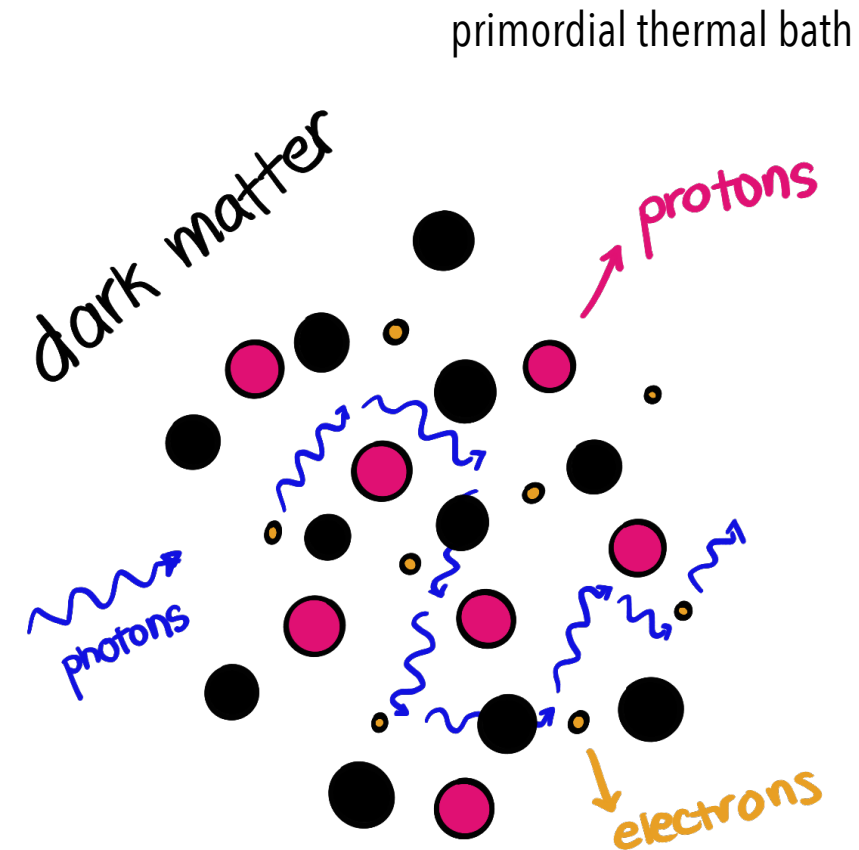
- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

$$\dot{n}_\chi + \boxed{3Hn_\chi} = - \langle \sigma_{\chi\bar{\chi}} v \rangle_{\text{eq}} \left[\boxed{n_\chi^2} - \boxed{n_{\chi,\text{eq}}^2} \right]$$

dilution due to expansion
DM annihilation
DM production

- Equilibrium number densities:

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \text{ relativistic} \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \text{ non-relativistic} \end{cases}$$



Particle cosmology: thermal freeze-out

- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

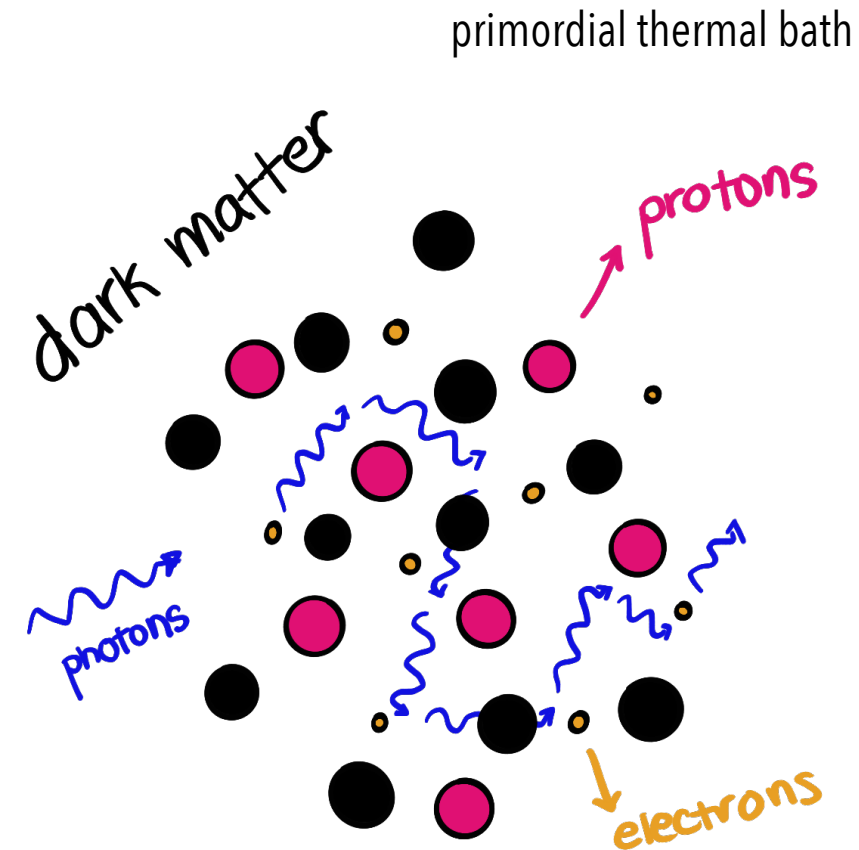
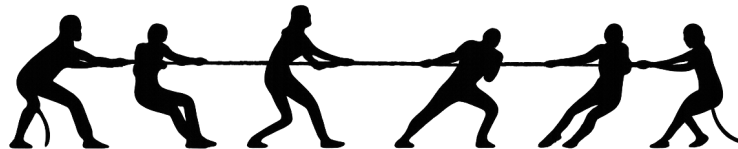
$$\dot{n}_\chi + \underbrace{3Hn_\chi}_{\text{dilution due to expansion}} = - \underbrace{\langle \sigma_{\chi\bar{\chi}} v \rangle_{\text{eq}}}_{\text{DM annihilation}} \underbrace{\left[n_\chi^2 - n_{\chi,eq}^2 \right]}_{\text{DM production}}$$

- Equilibrium number densities:

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \text{ relativistic} \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \text{ non-relativistic} \end{cases}$$

Hubble expansion

H^{-1} = characteristic expansion time



Particle cosmology: thermal freeze-out

- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

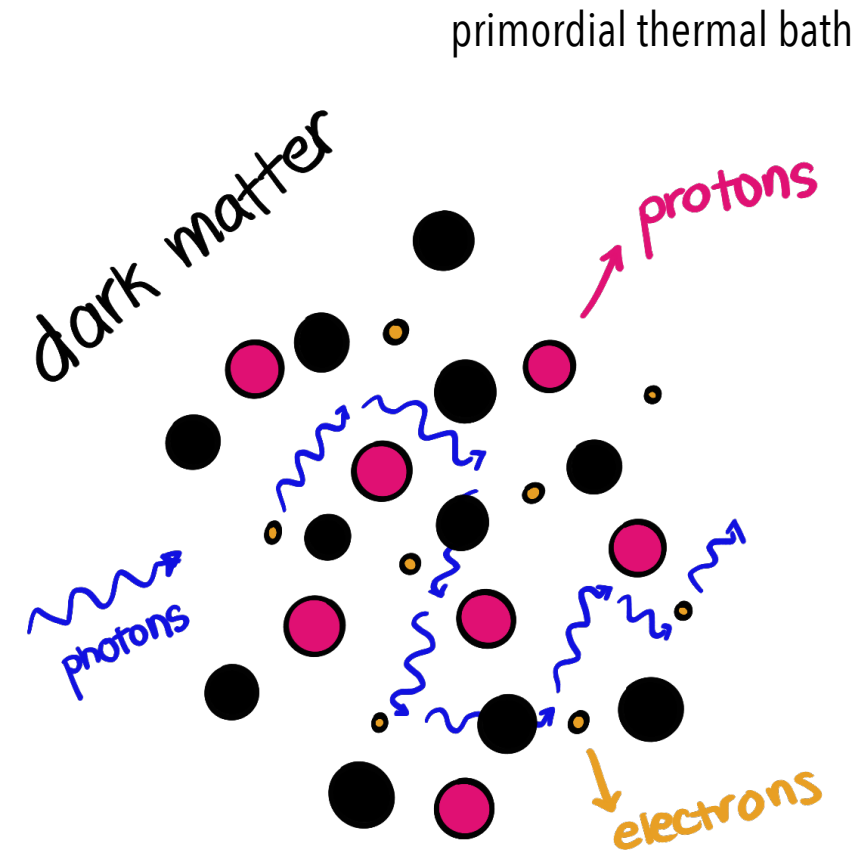
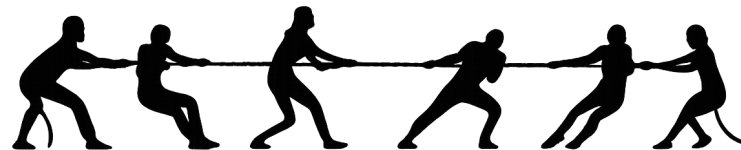
$$\dot{n}_\chi + \underbrace{3Hn_\chi}_{\text{dilution due to expansion}} = - \langle \sigma_{\chi\bar{\chi}} v \rangle_{\text{eq}} \underbrace{\left[n_\chi^2 - n_{\chi,\text{eq}}^2 \right]}_{\text{DM production}} \quad \text{DM annihilation}$$

- Equilibrium number densities:

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \text{ relativistic} \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \text{ non-relativistic} \end{cases}$$

Hubble expansion

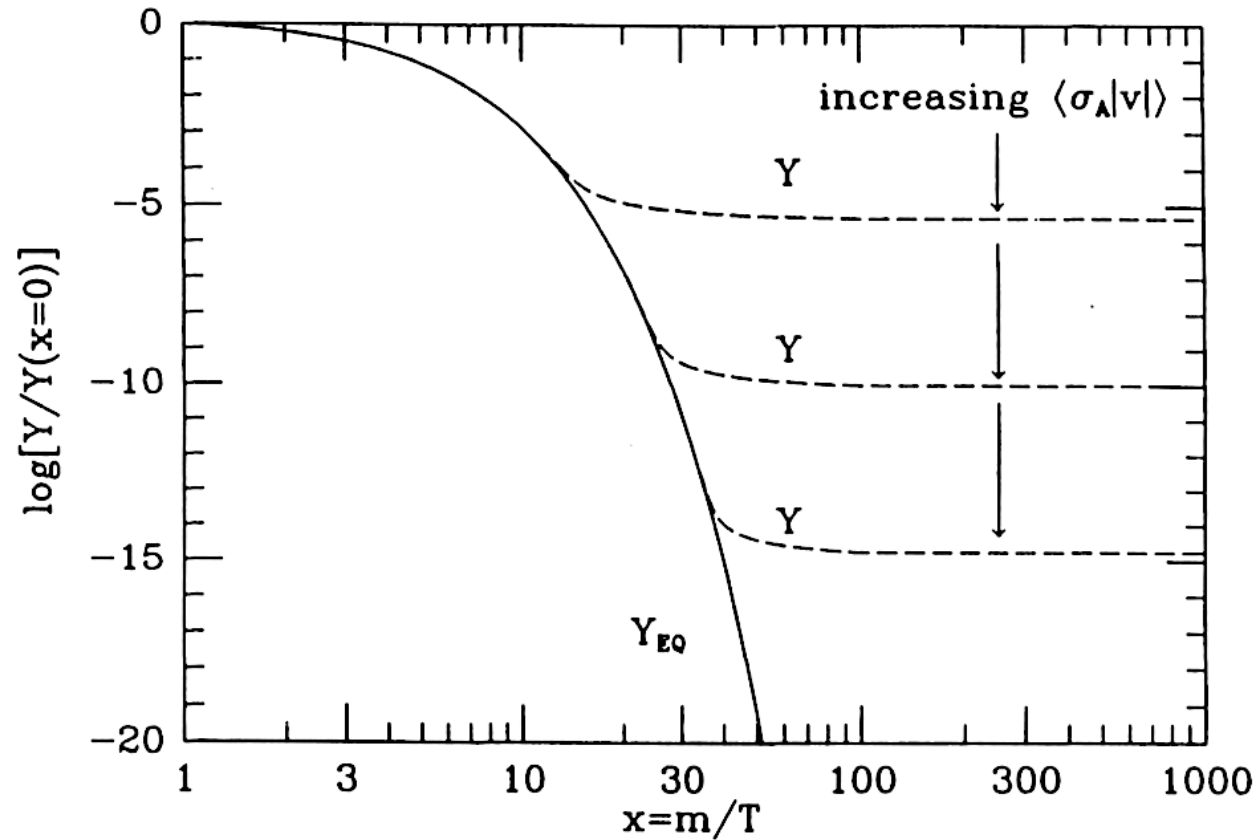
H^{-1} = characteristic expansion time



Annihilation rate

$\Gamma^{-1} = 1/n_\chi \langle \sigma v \rangle =$
time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3$$

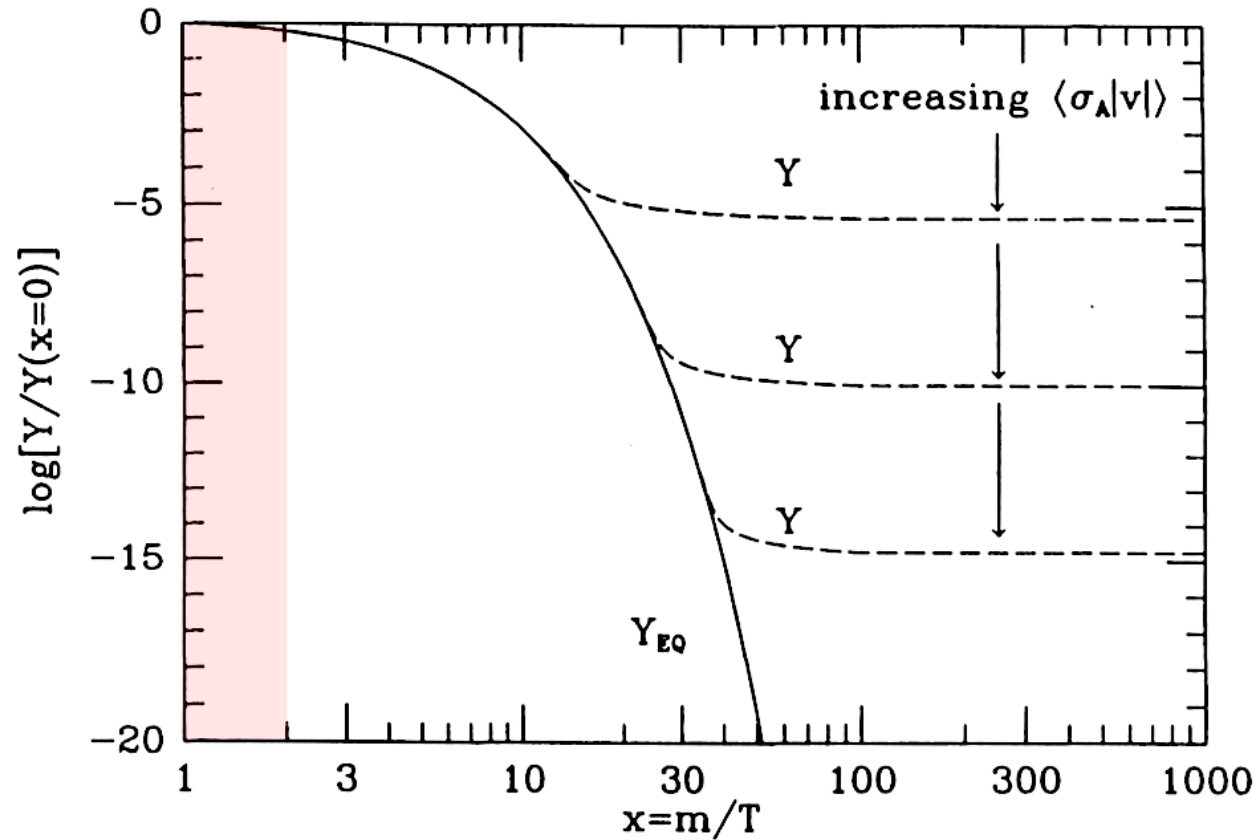
Hubble expansion

H^{-1} = characteristic expansion time

Annihilation rate

$\Gamma^{-1} = 1/n_\chi \langle \sigma v \rangle =$
time for a particle to annihilate

Particle cosmology: thermal freeze-out



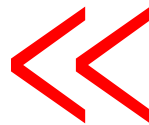
comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 \sim \text{const}$$

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \end{cases}$$

Hubble expansion

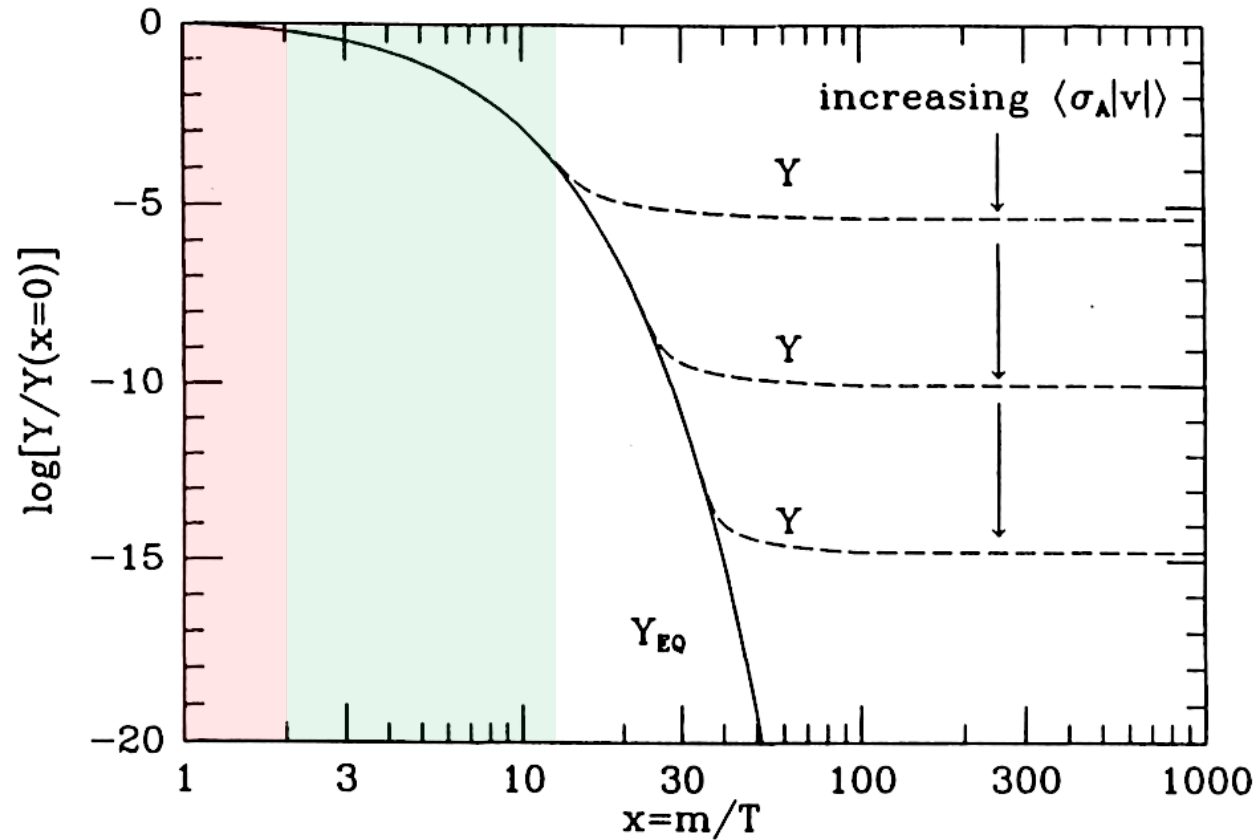
H^{-1} = characteristic expansion time



Annihilation rate

$\Gamma^{-1} = 1/n_\chi \langle\sigma v\rangle =$
time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 \sim e^{-m_\chi/T}$$

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \end{cases}$$

Hubble expansion

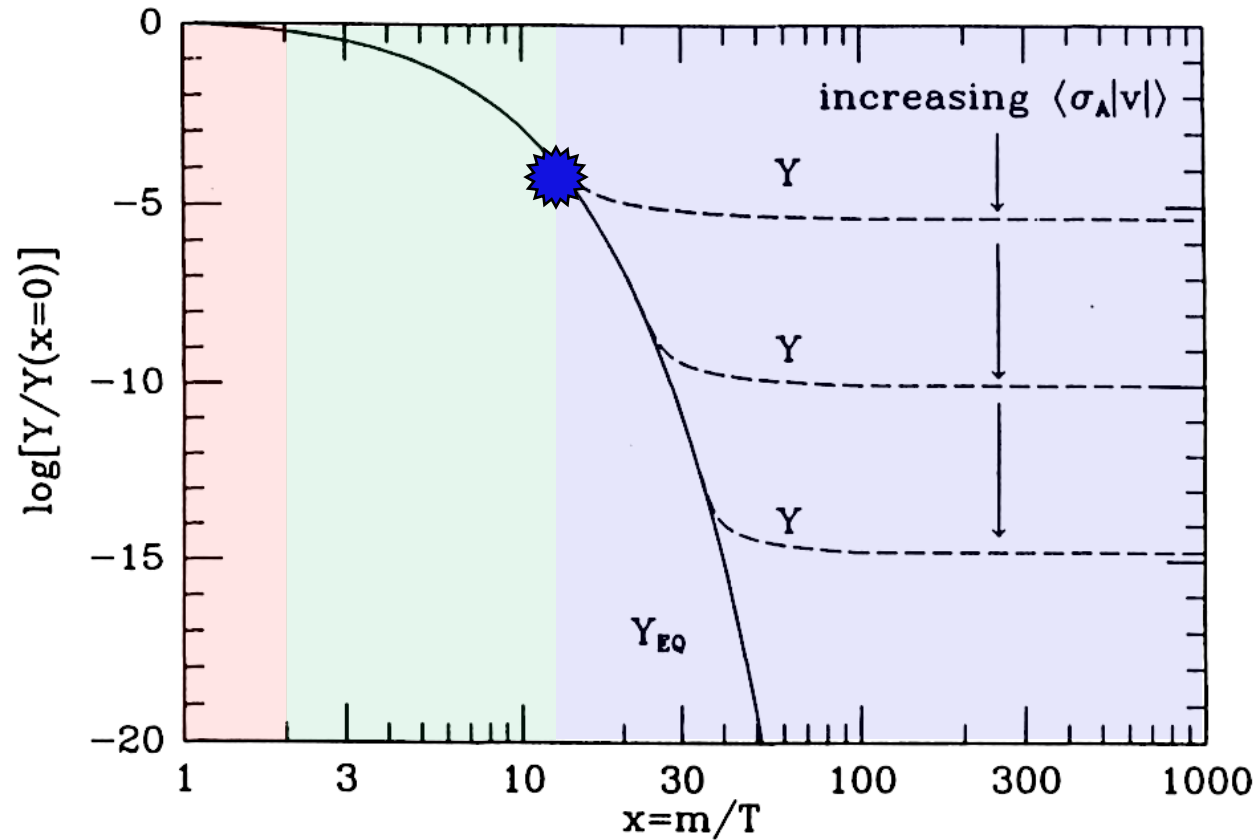
H^{-1} = characteristic expansion time

$\sim$

Annihilation rate

$\Gamma^{-1} = 1/n_\chi \langle \sigma v \rangle =$
time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 = Y_0$$

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \end{cases}$$

freeze-out

Hubble expansion

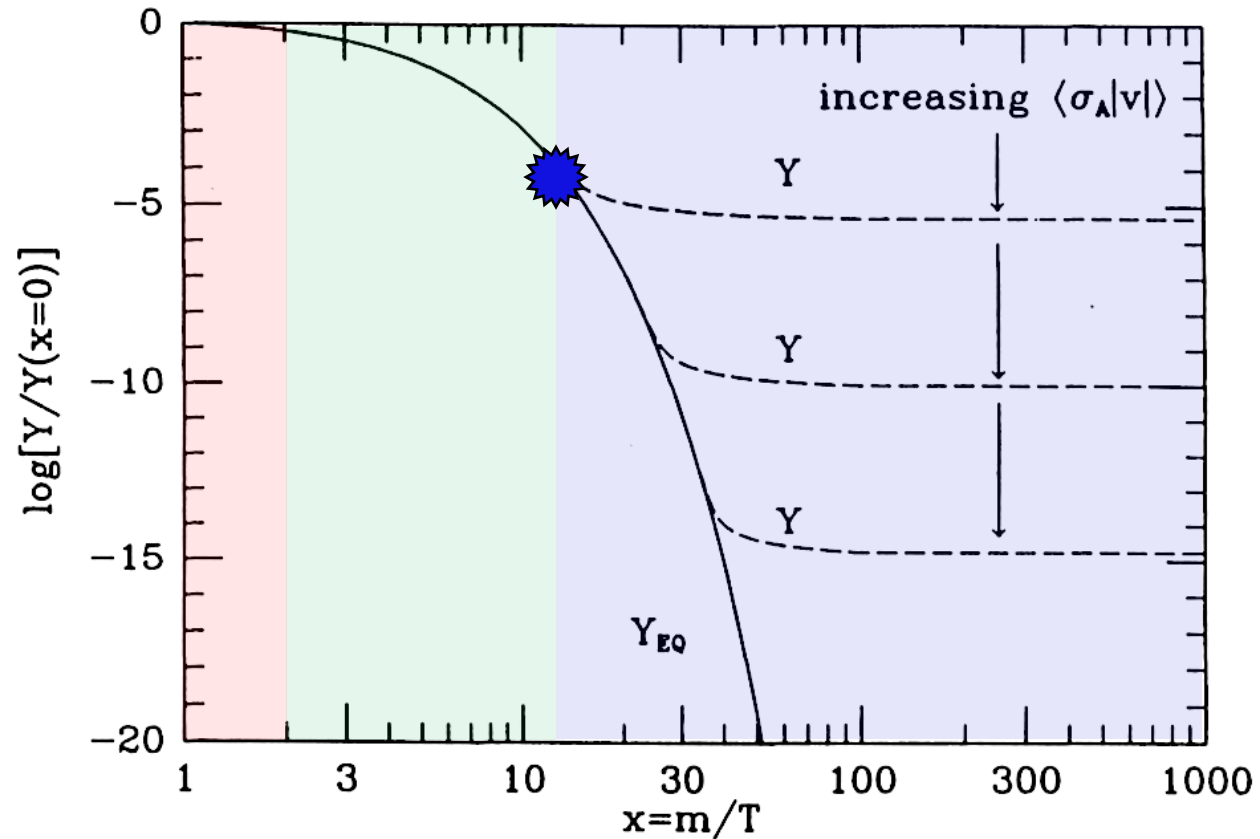
H^{-1} = characteristic expansion time



Annihilation rate

$\Gamma^{-1} = 1/n_\chi \langle \sigma v \rangle =$
time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 = Y_0$$

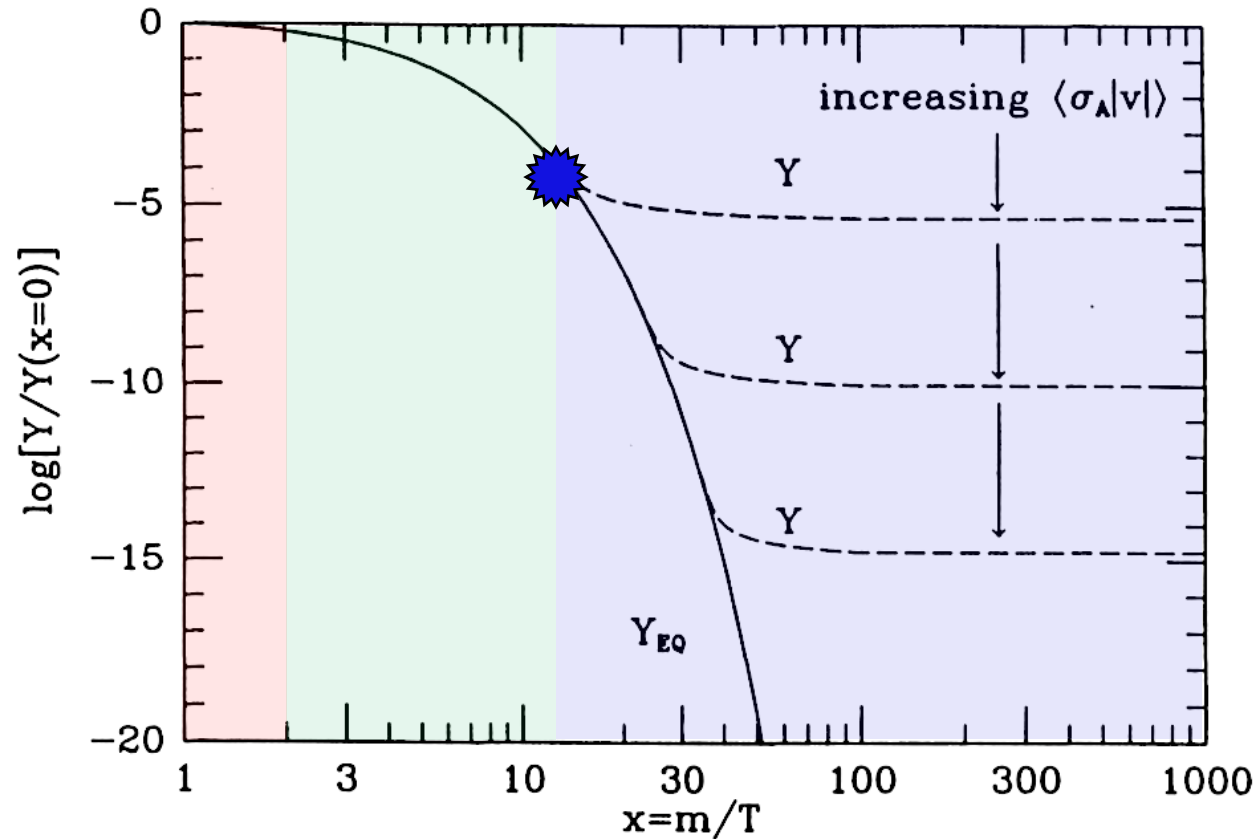
$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \end{cases}$$

freeze-out

- freeze-out leaves a relic abundance controlled primarily by $\langle\sigma v\rangle$

$$\Omega_\chi h^2 \approx 0.12 \times 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} / \langle\sigma v\rangle$$

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 = Y_0$$

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4} \frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \\ g \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \end{cases}$$

freeze-out

WIMP miracle

- freeze-out leaves a relic abundance controlled primarily by $\langle \sigma v \rangle$

$$\Omega_\chi h^2 \approx 0.12 \times 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} / \langle \sigma v \rangle$$

$$\langle \sigma v \rangle \sim 1 \text{ pb } c (200 \text{ GeV}/m_{DM})^2 \text{ (weak scale estimate)} \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

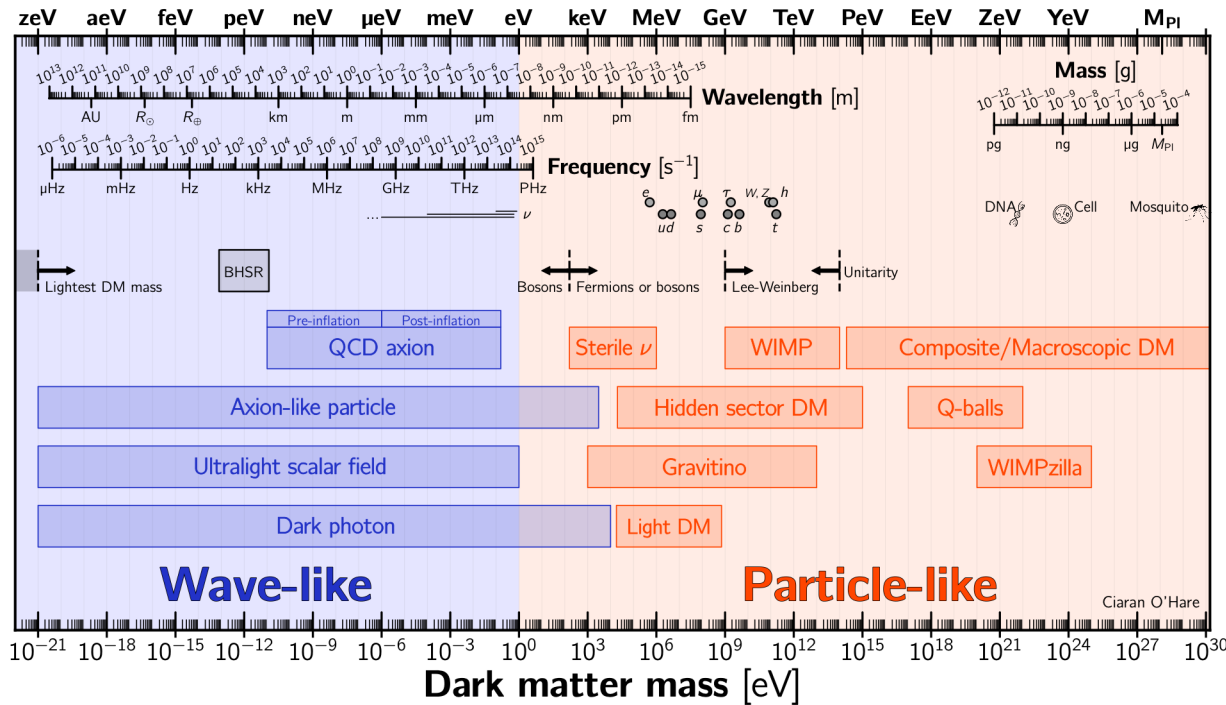
Too light: has wave-like properties on galactic scales



Dark Matter Landscape: A Theorist's View

Dark matter spans over
80 orders of magnitude in
mass (+ interaction strength)

[Ciaran A. J. O'Hare]

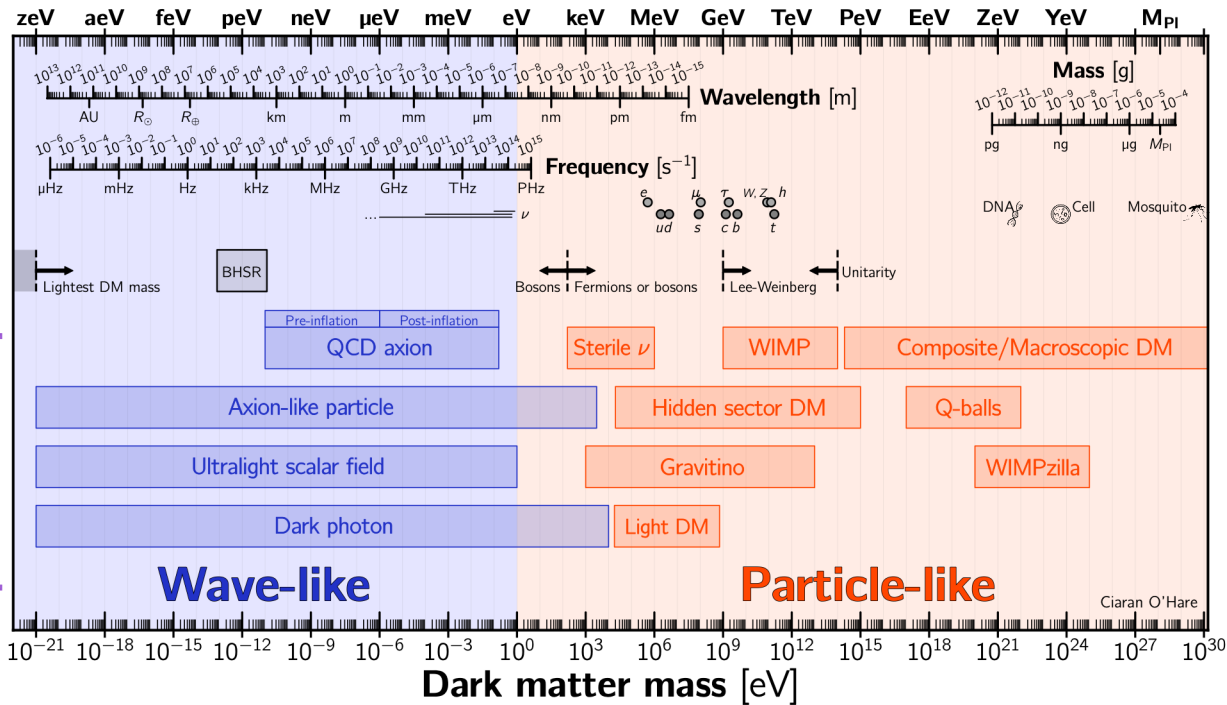



proton
 $m \sim 10^{-27}$ kg



(c) Pablo Carlos Budassi

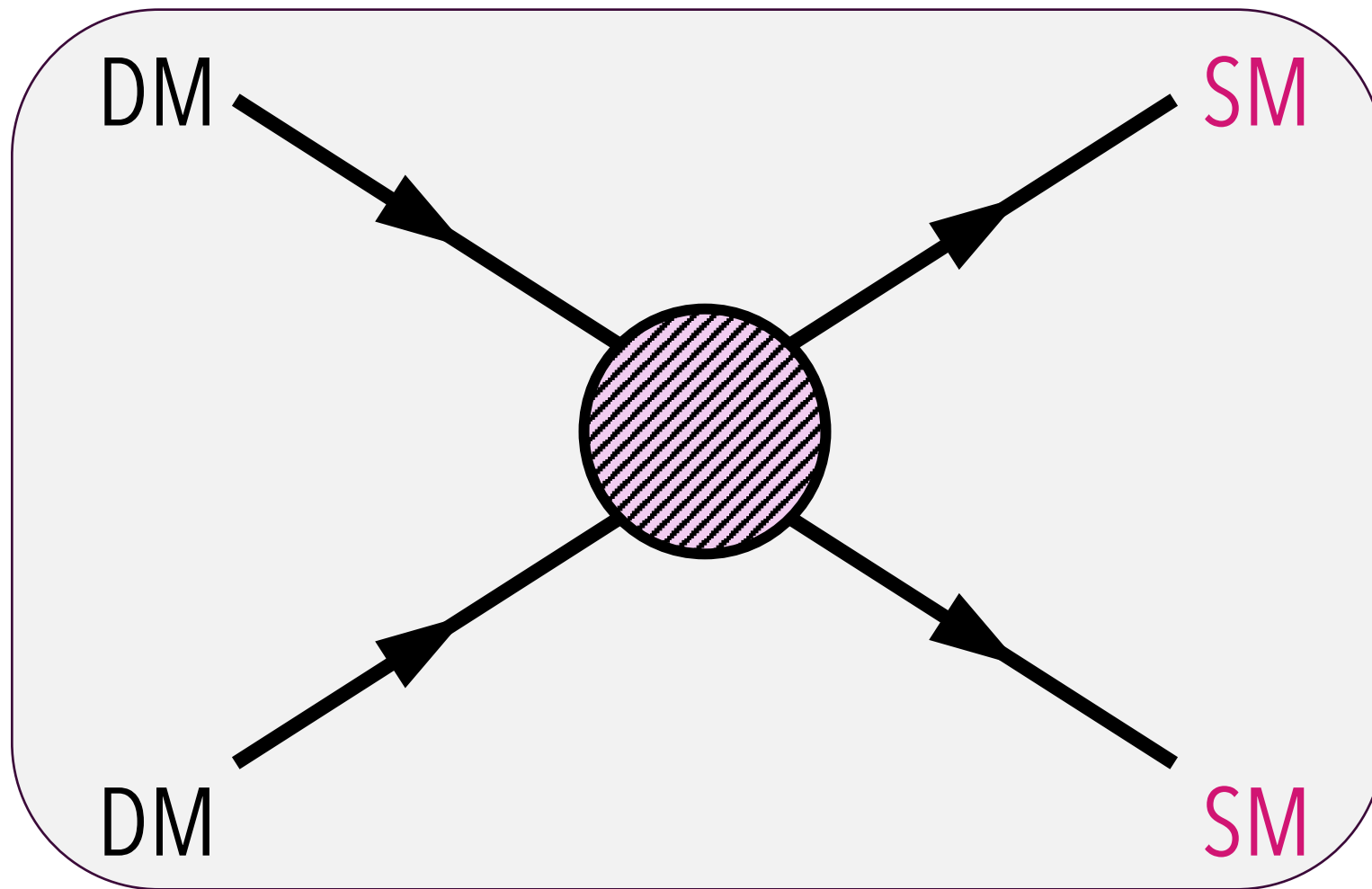
Dark Matter Landscape: A Theorist's View



Our search strategies are
inherently biased

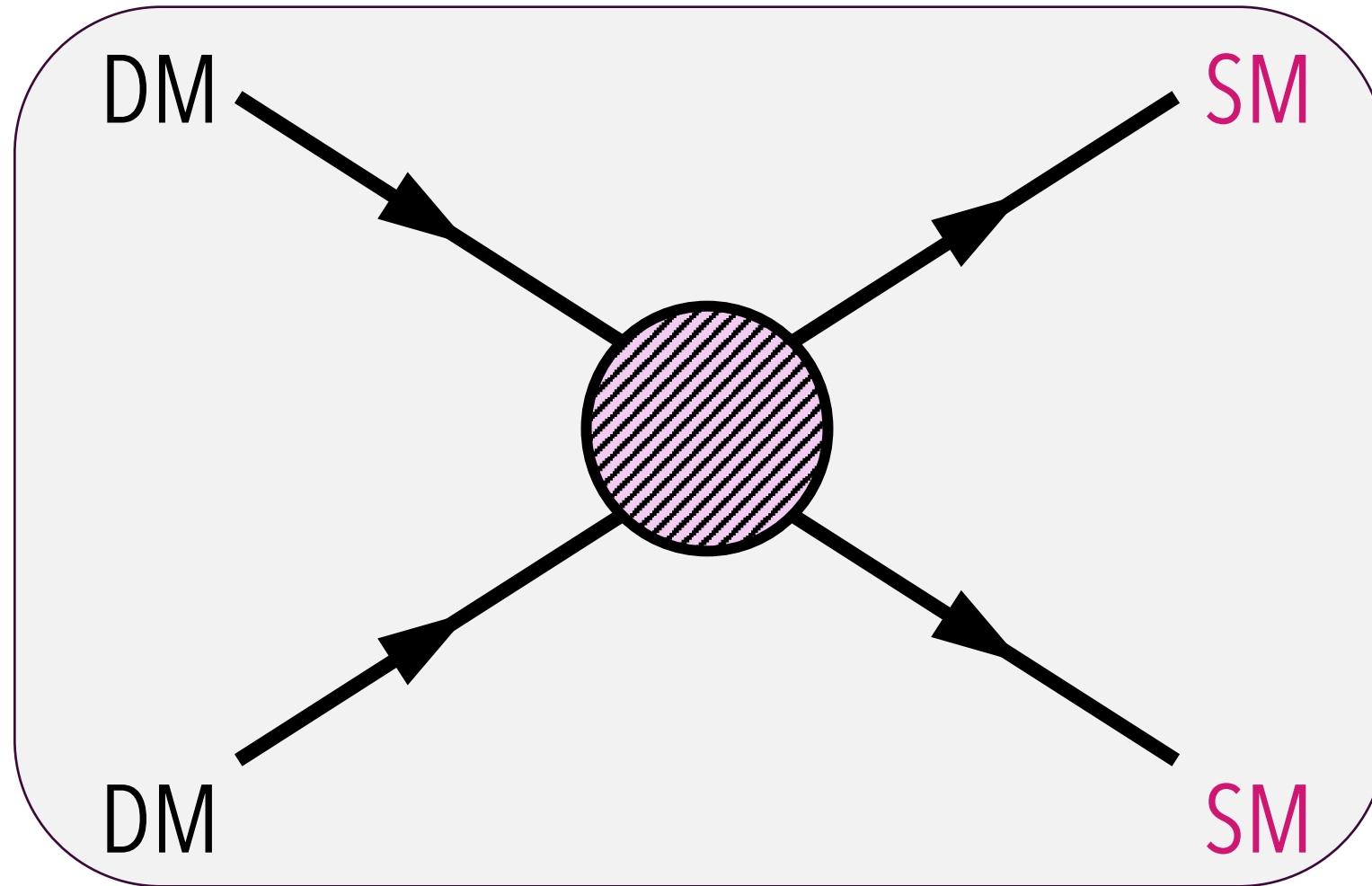
1. **model dependency bias:** theory guides our search strategies
2. **observational bias:** disparity between the data we have and the data we need
3. **identifiable signature bias:** required for observation

Detection strategies



Collider Searches

"Make it"



Collider searches:

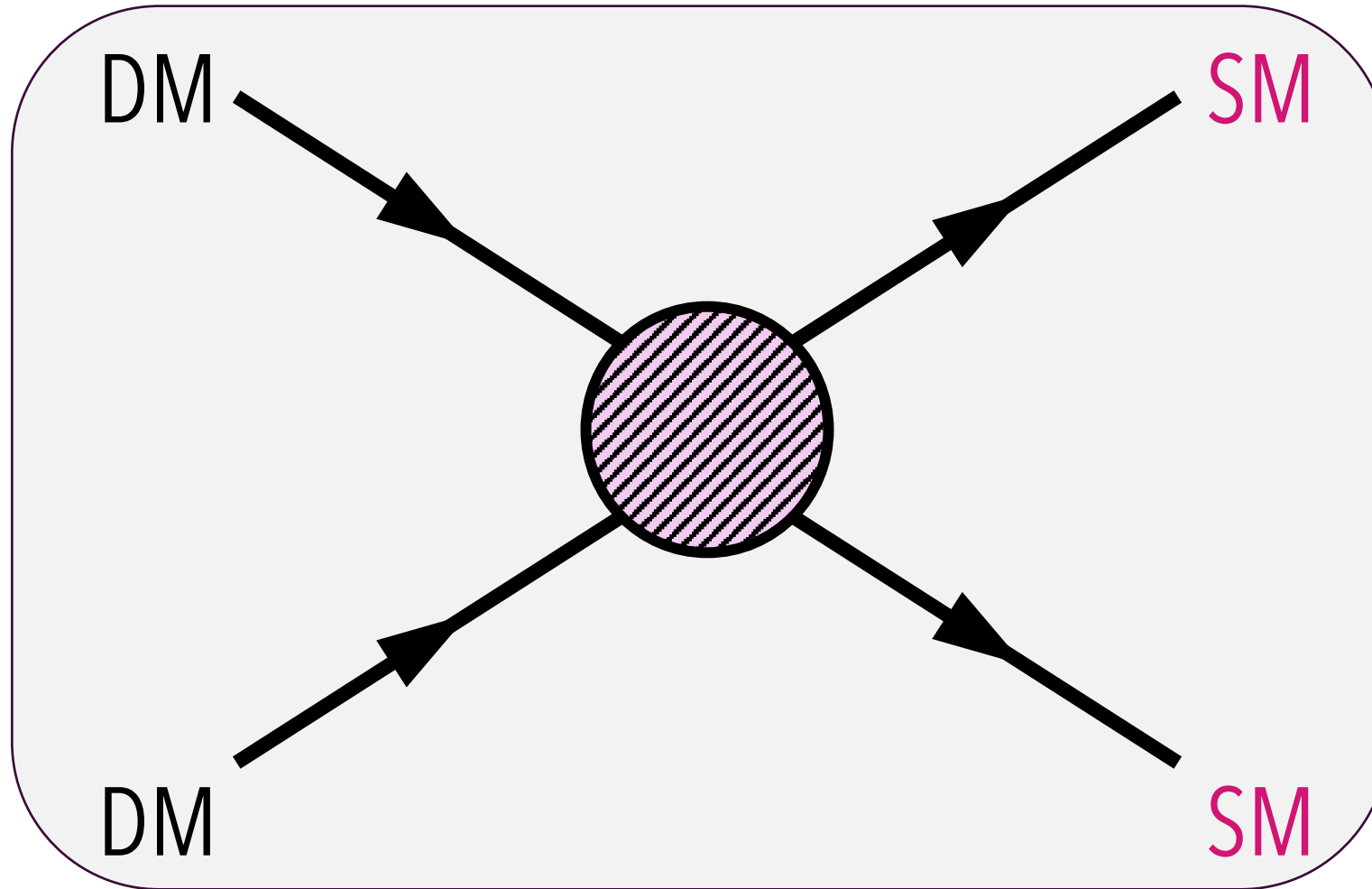
Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

Direct Detection
"Shake it"



Collider Searches

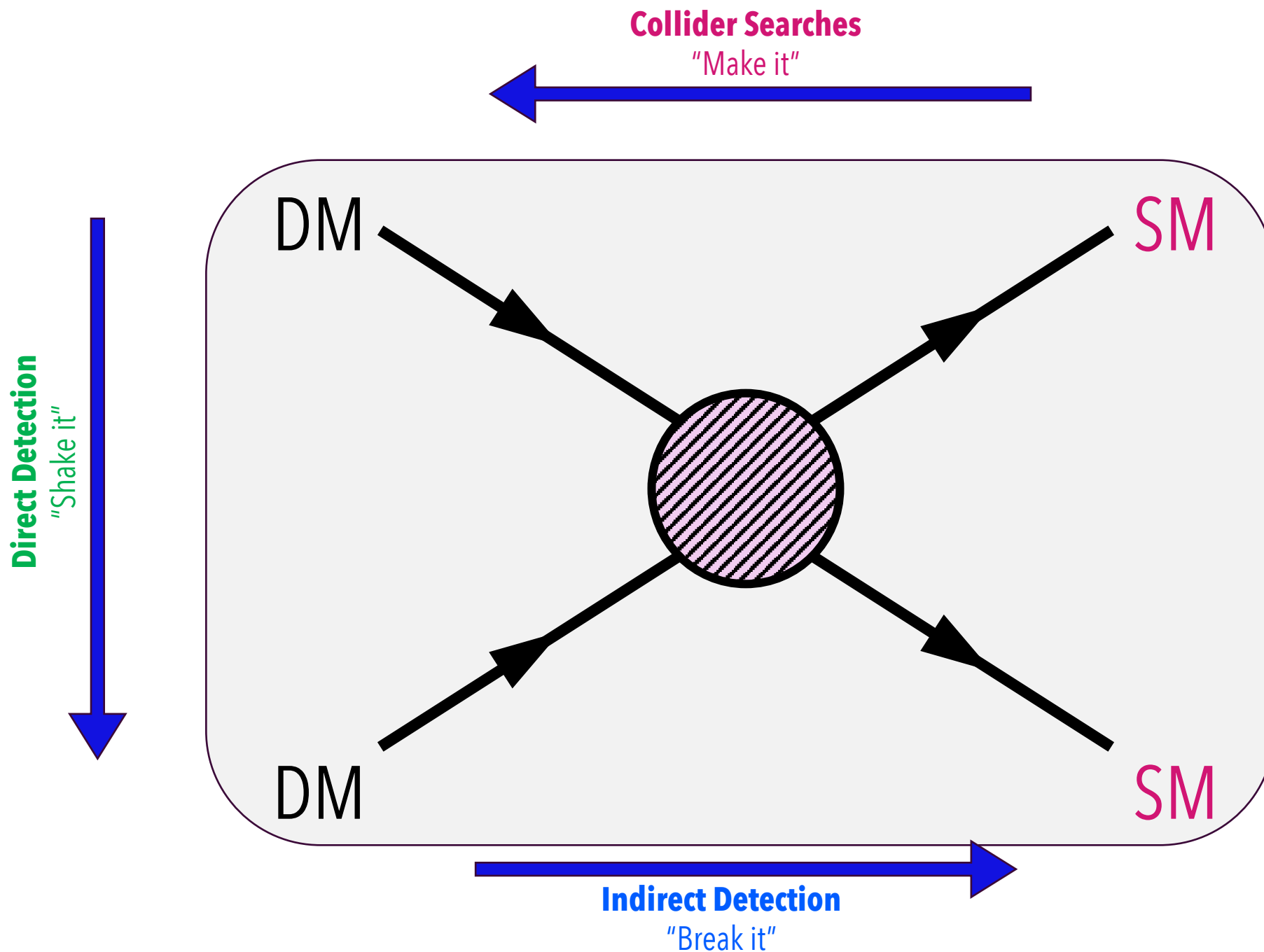
"Make it"



Collider searches:

Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

Direct detection: Look for DM scattering off nuclei or electrons in low-background detectors as Milky Way halo dark matter passes through Earth.



Collider searches:

Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

Direct detection: Look for DM scattering off nuclei or electrons in low-background detectors as Milky Way halo dark matter passes through Earth.

Indirect detection: Look for SM particles produced by DM, for example through annihilation or decay, in the Milky Way and other astrophysical systems.

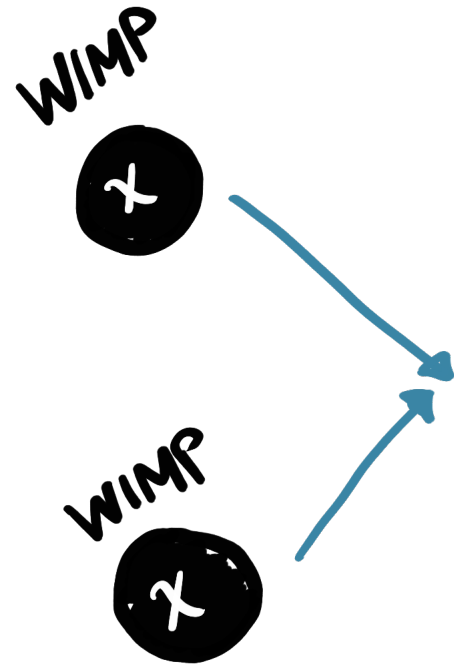
Indirect detection formalism

→ Searching for the contribution of DM annihilation to the astrophysical flux of photons, neutrinos and charged particles

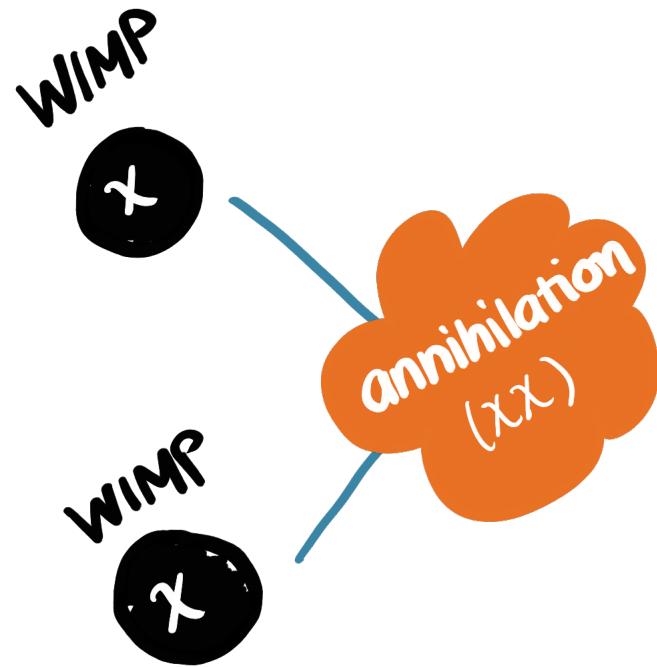
Indirect observables



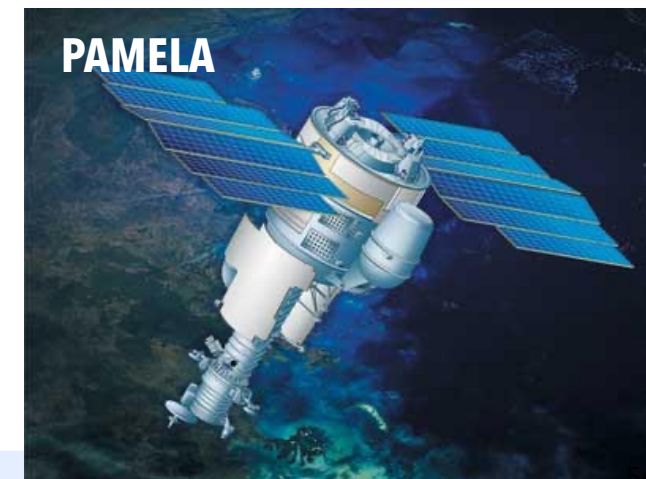
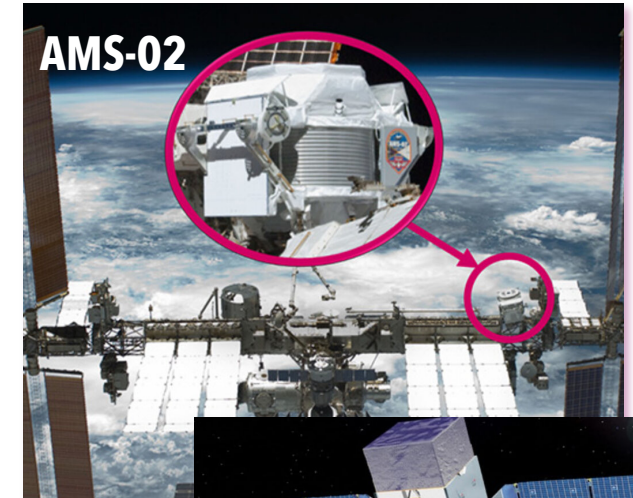
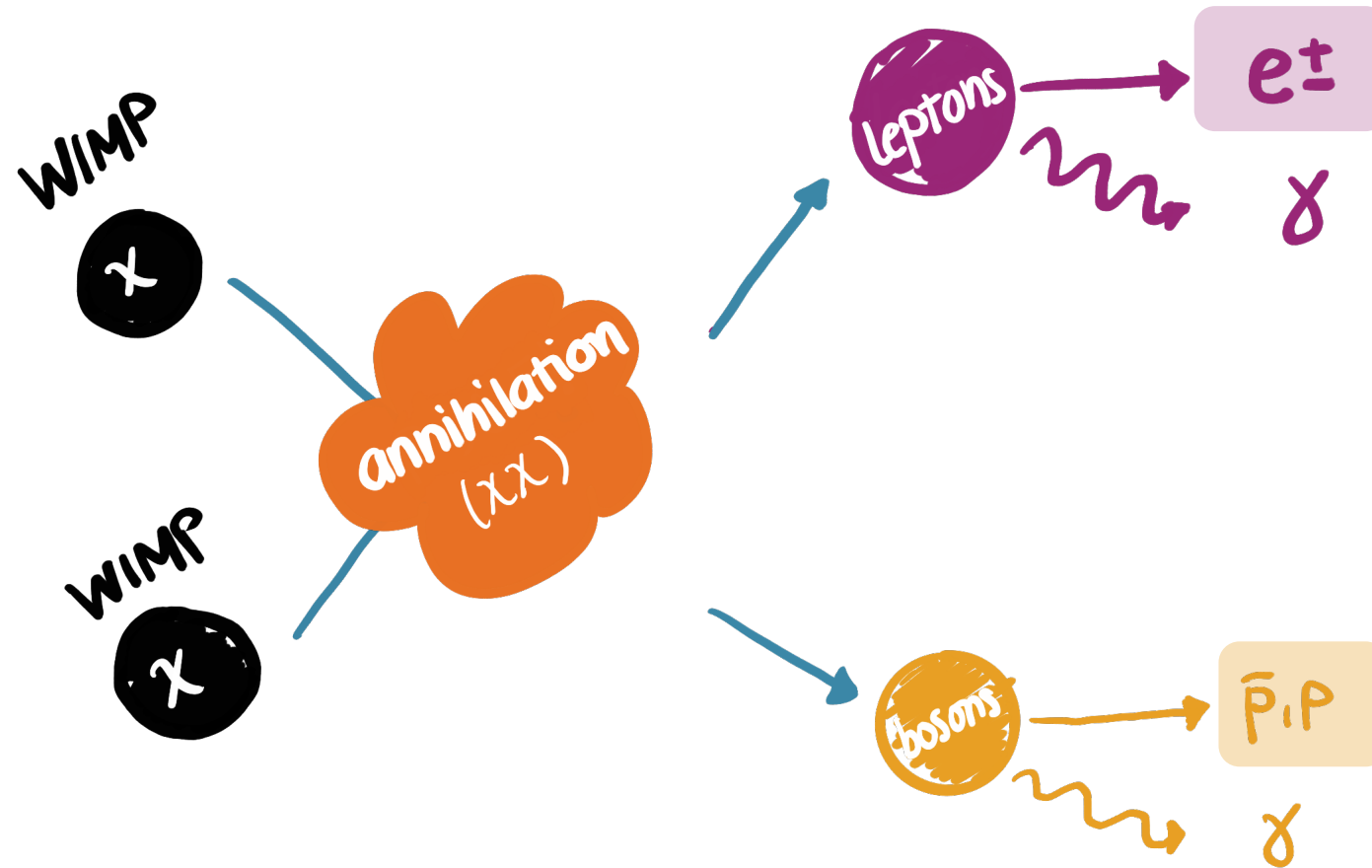
Indirect observables



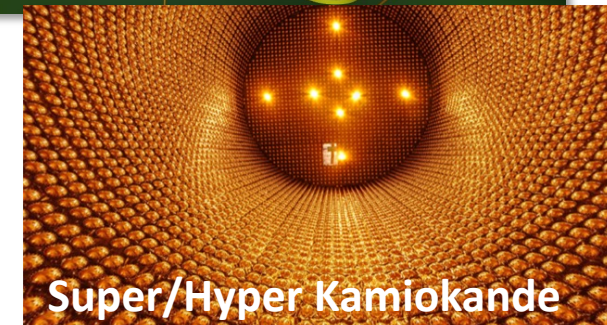
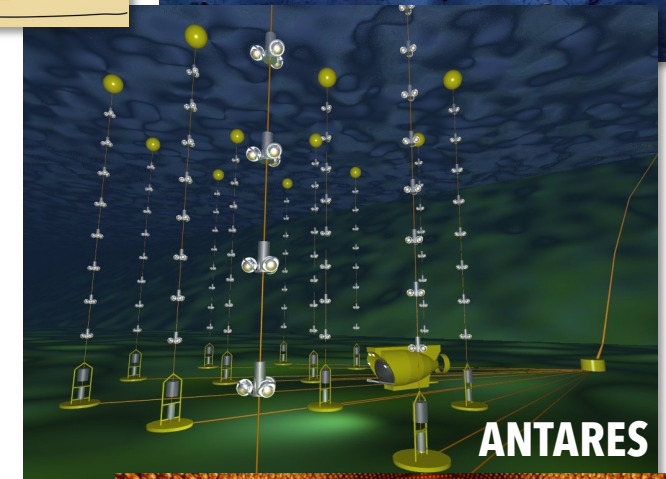
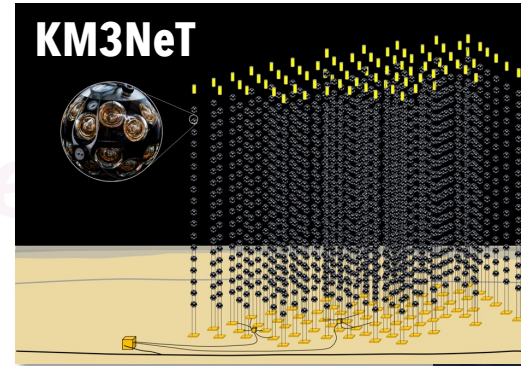
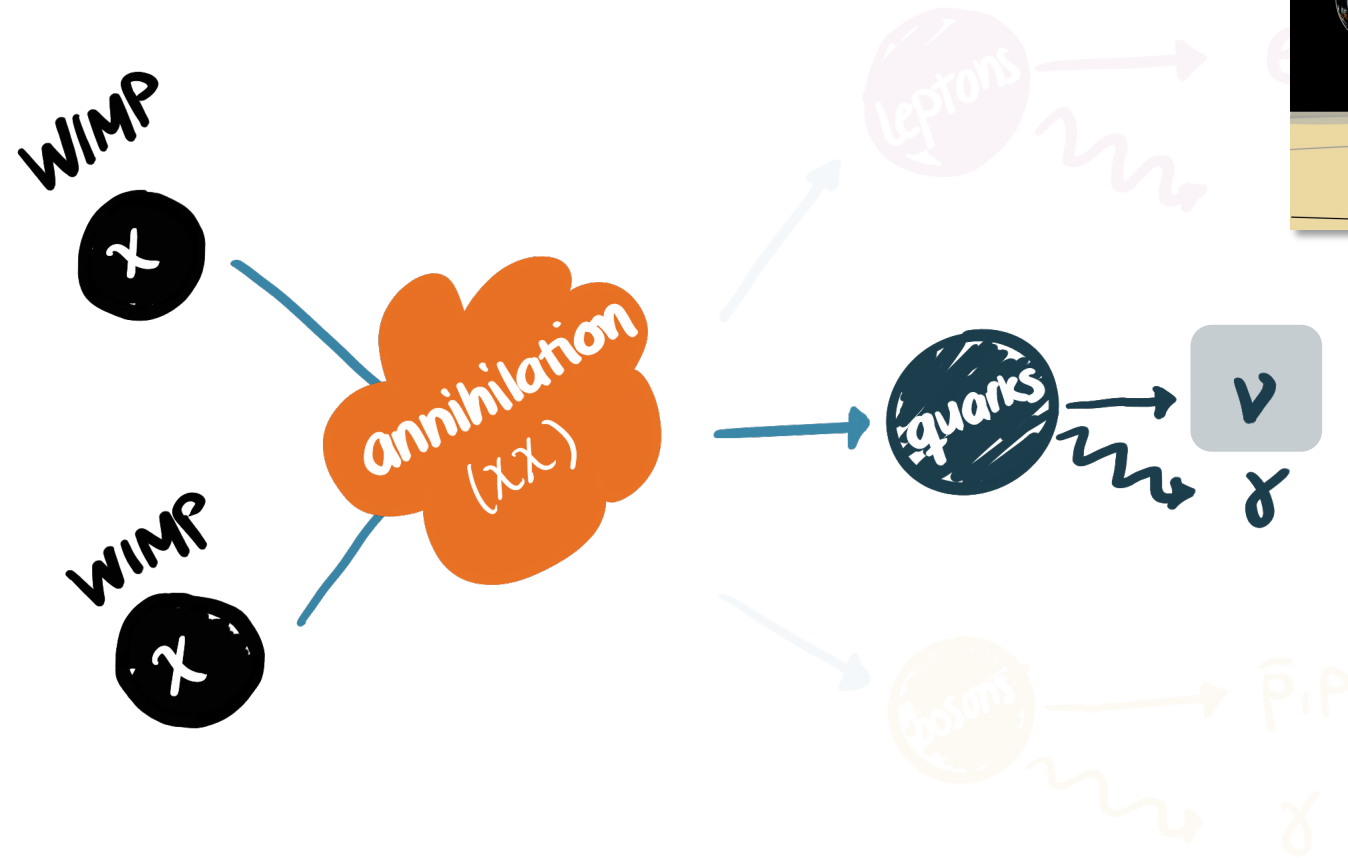
Indirect observables



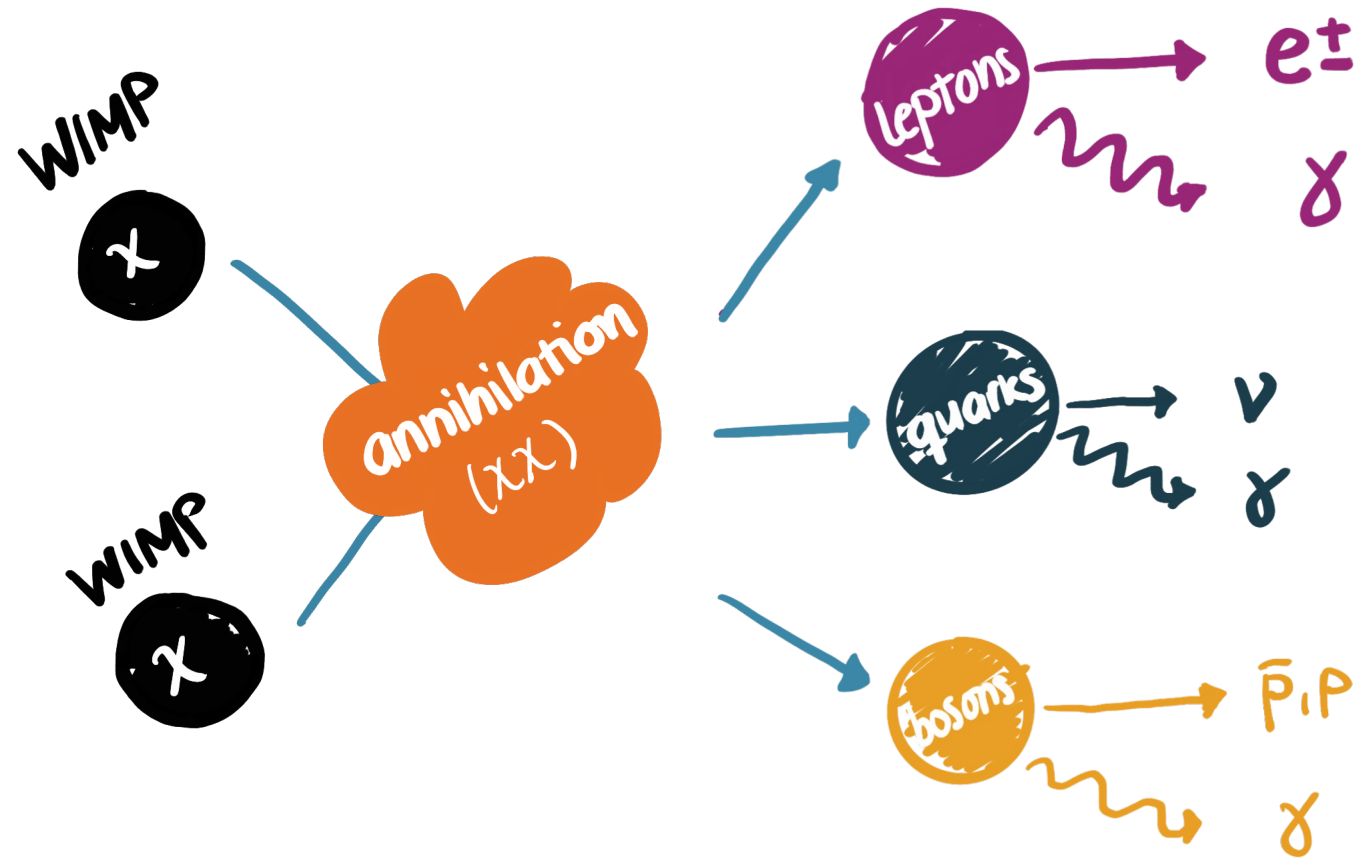
Indirect observables



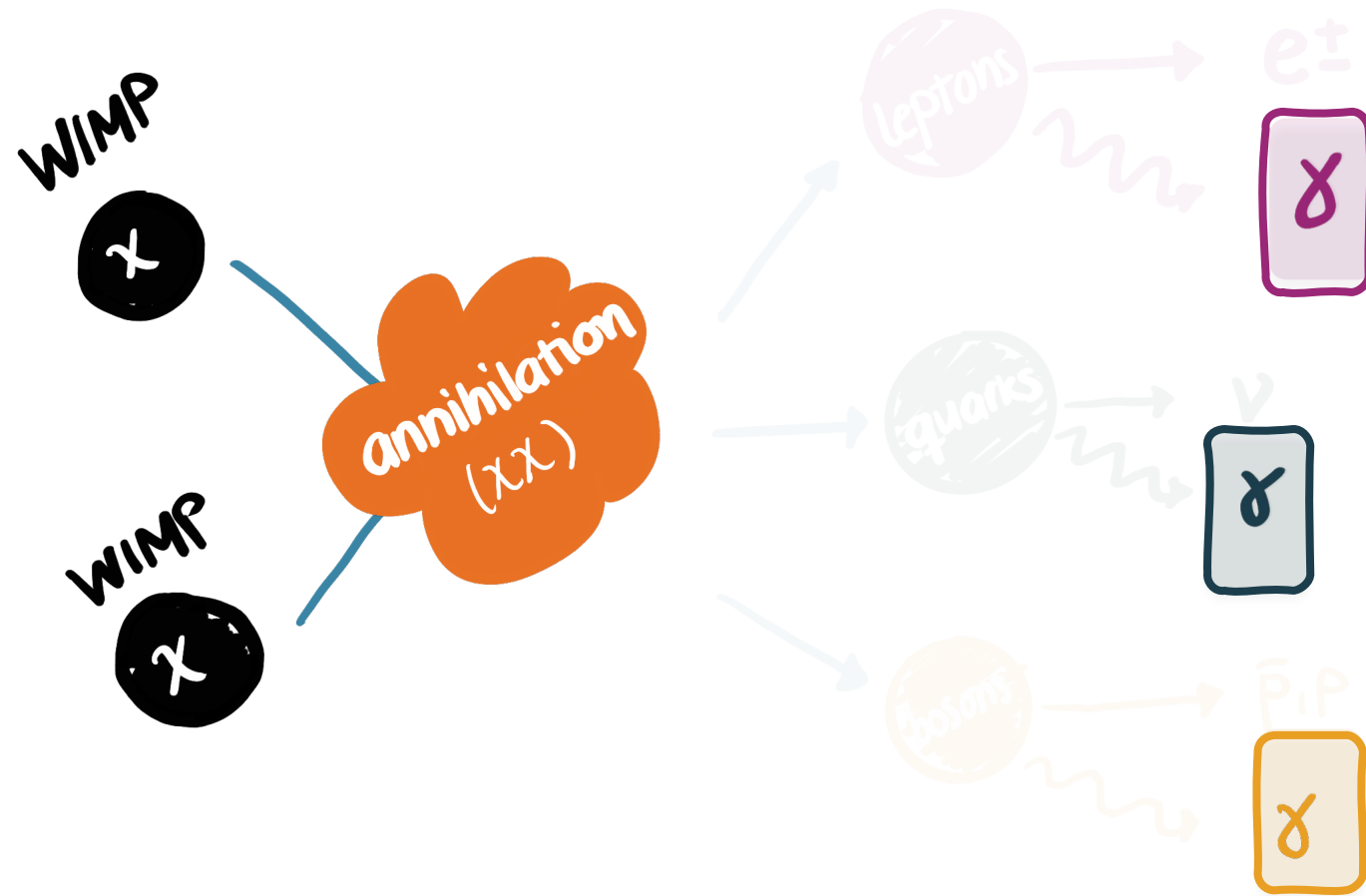
Indirect observables



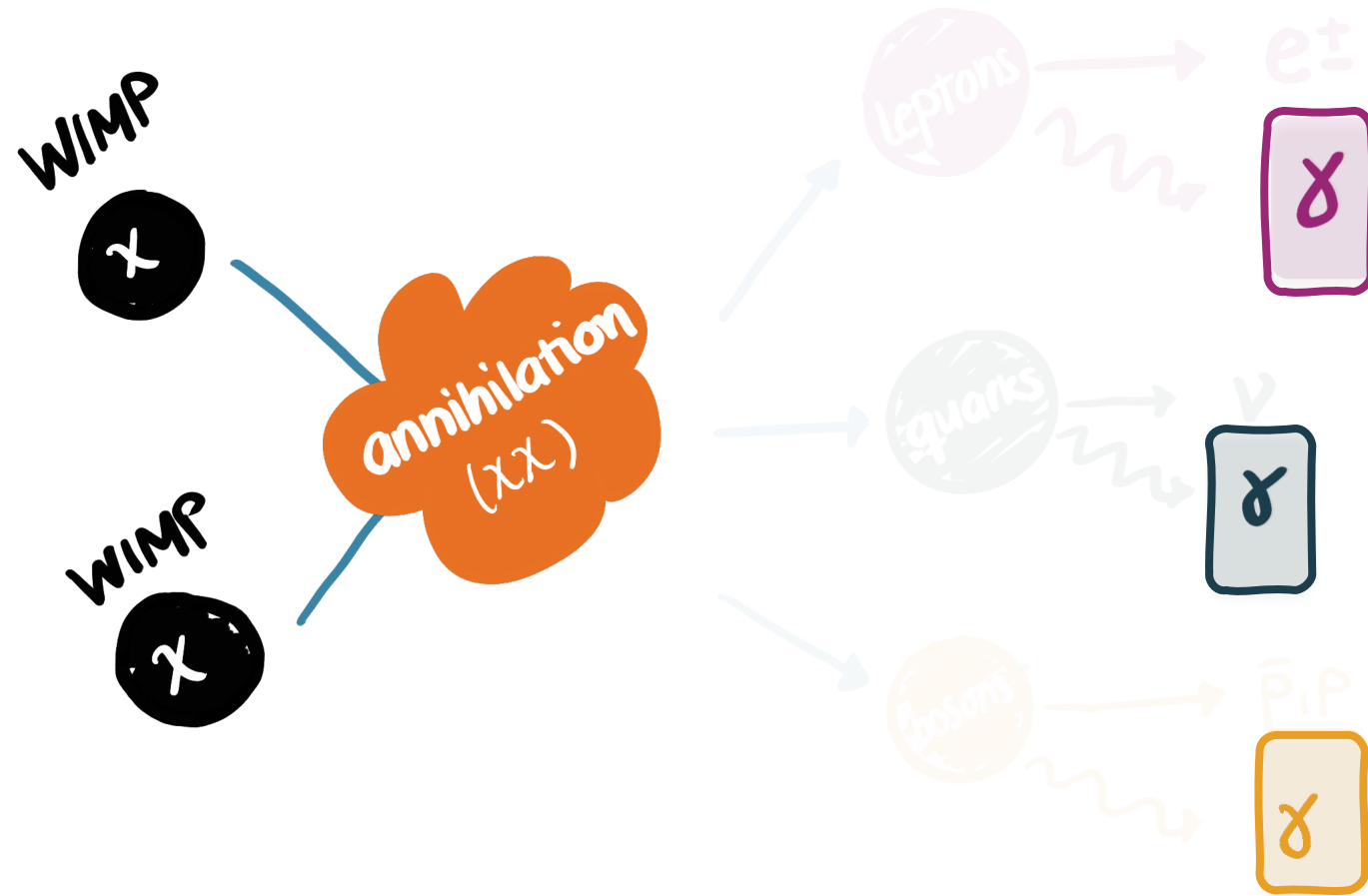
Indirect observables



Indirect observables



Indirect observables



MAGIC



VERITAS



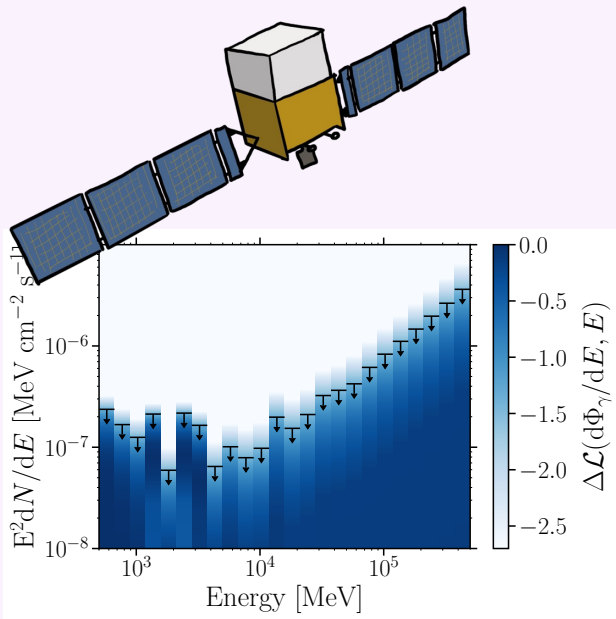
HAWC



Dark Matter signal: what do we observe?

DM flux

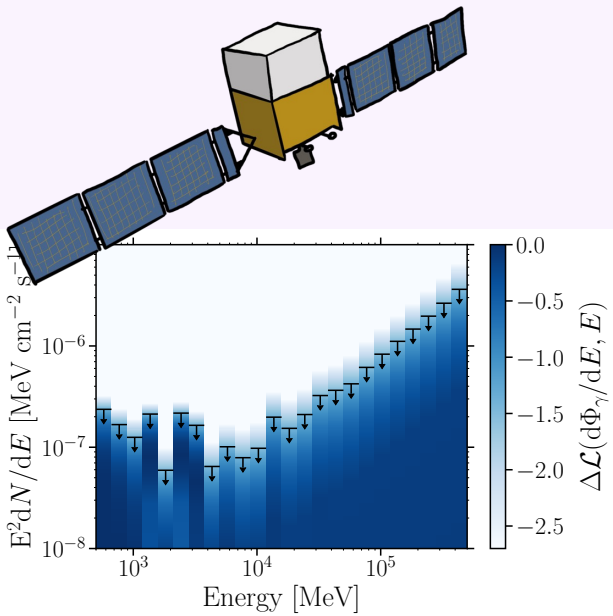
$$\frac{d\Phi}{dE}$$



Dark Matter signal: what do we observe?

DM flux

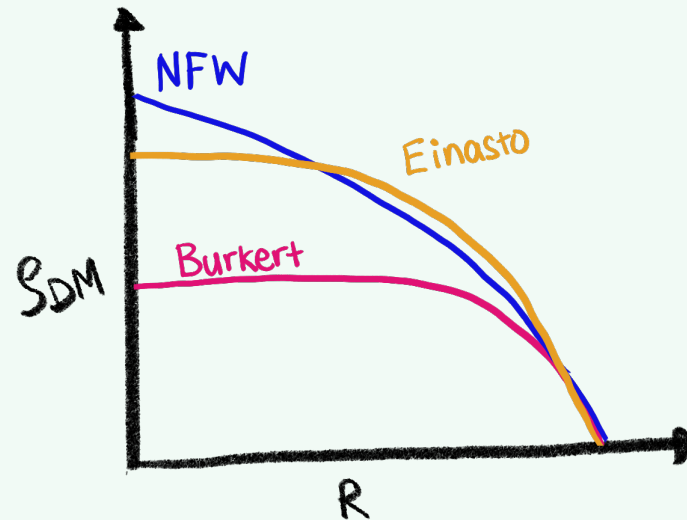
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

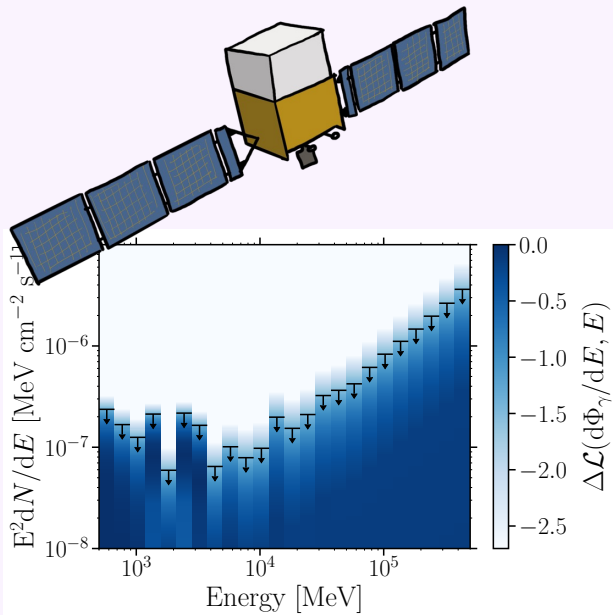
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



Dark Matter signal: what do we observe?

DM flux

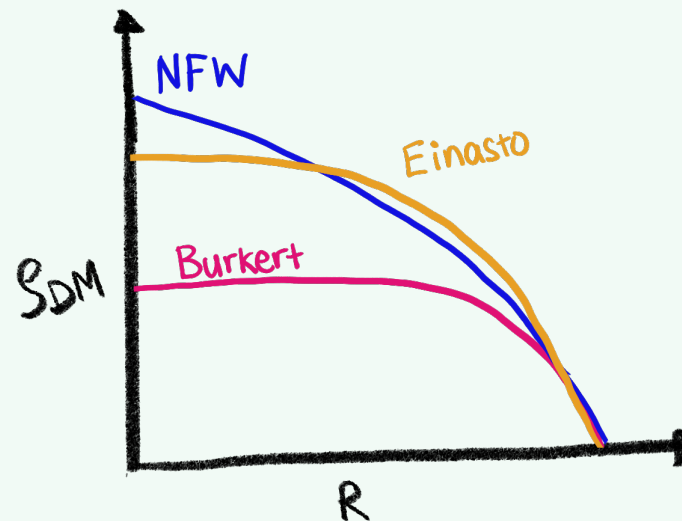
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

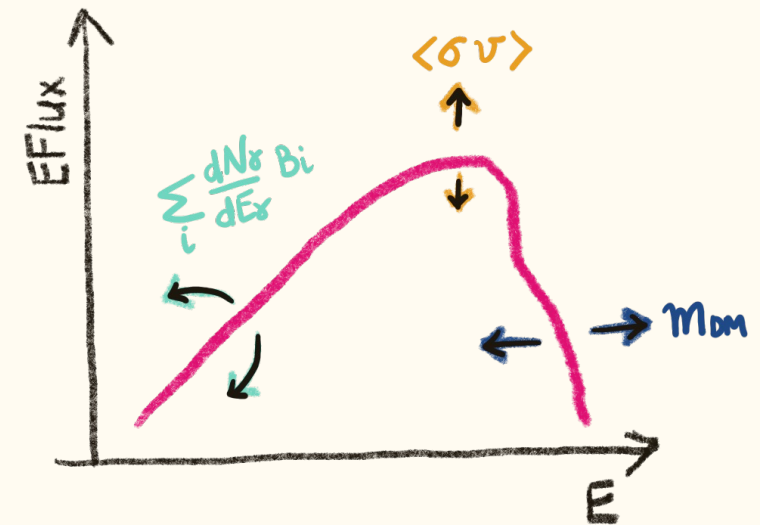
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

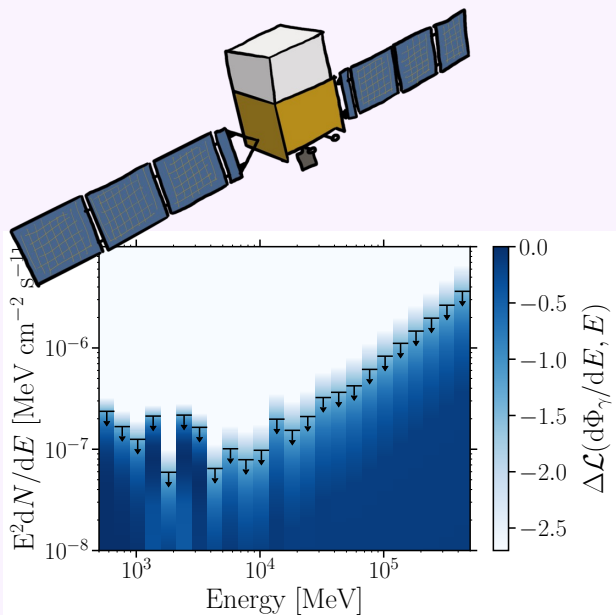
$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



Dark Matter signal: what do we observe?

DM flux

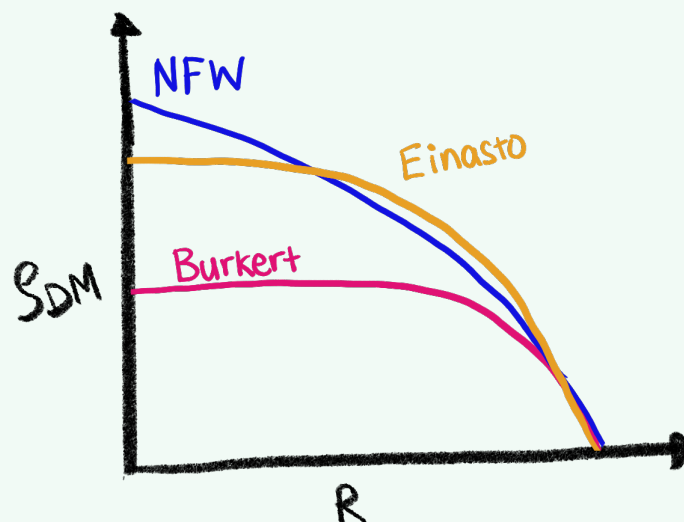
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

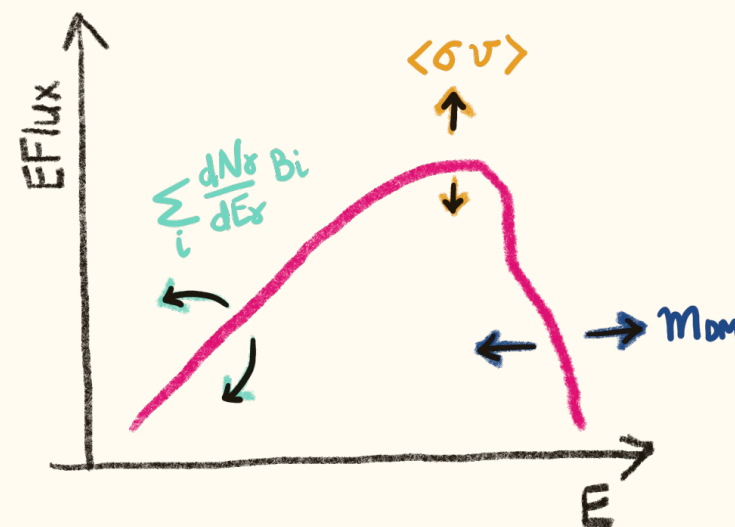
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



J-factors, D-factors, and density profiles

The astrophysical contribution to the flux depends entirely on the dark-matter distribution.

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}^2(r(\ell, \theta)) d\ell$$

$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}(r(\ell, \theta)) d\ell$$

Q2. Annihilation J-factor scales with ρ_{DM}^2 , but decay D-factor scales only with ρ_{DM} . Why?

J-factors, D-factors, and density profiles

The astrophysical contribution to the flux depends entirely on the dark-matter distribution.

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}^2(r(\ell, \theta)) d\ell$$

[Submitted on 13 Nov 1996 (v1), last revised 21 Oct 1997 (this version, v4)]

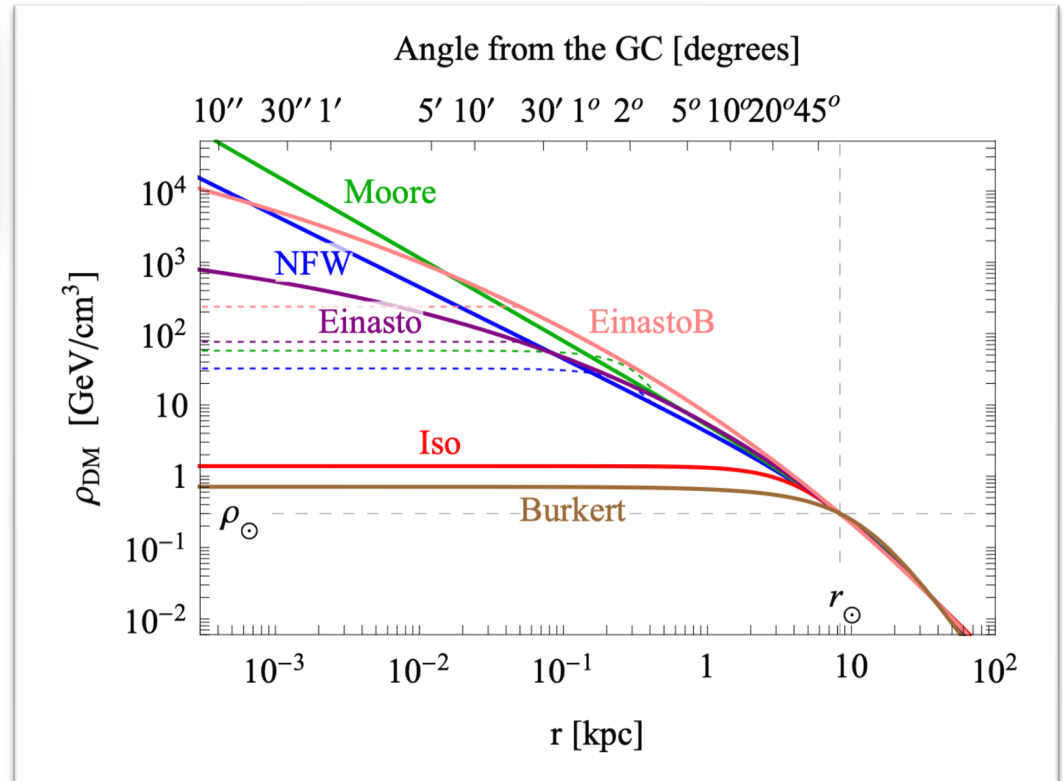
A Universal Density Profile from Hierarchical Clustering

Julio F. Navarro (Steward Observatory, University of Arizona), Carlos S. Frenk (University of Durham), Simon D.M. White (MPI fur Astrophysik)

But what is $\rho_{DM}(r)$?

- **Cuspy:** NFW, Einasto, Moore
- **Cored:** Burkert, isothermal
- Profiles can agree near the Solar position but differ dramatically toward the **Galactic Center**

$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}(r(\ell, \theta)) d\ell$$



J-factors, D-factors, and density profiles

The astrophysical contribution to the flux depends entirely on the dark-matter distribution.

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}^2(r(\ell, \theta)) d\ell$$

[Submitted on 13 Nov 1996 (v1), last revised 21 Oct 1997 (this version, v4)]

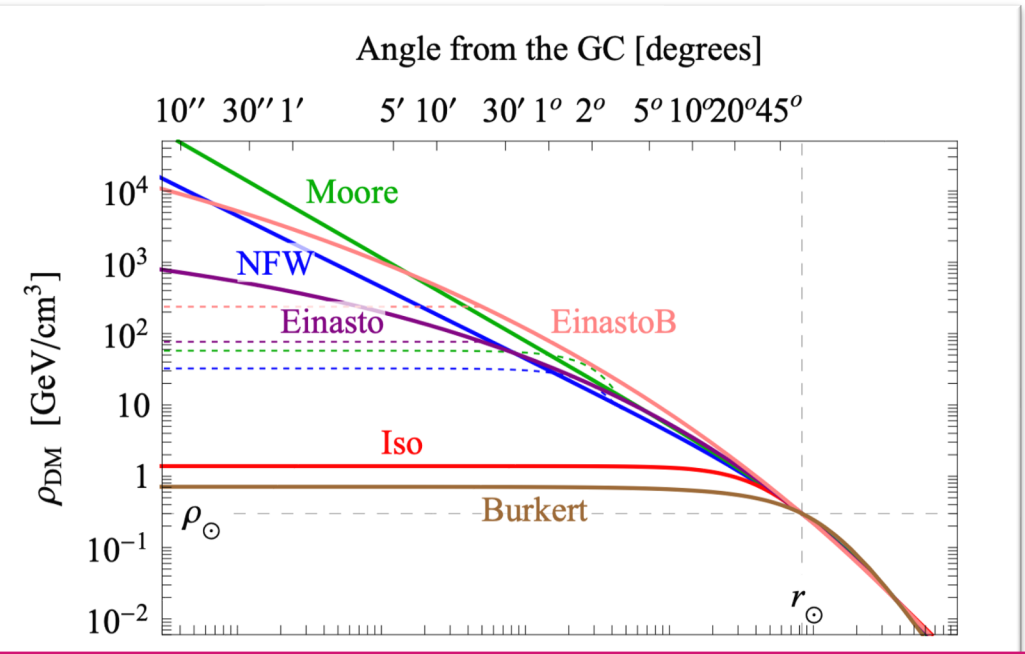
A Universal Density Profile from Hierarchical Clustering

Julio F. Navarro (Steward Observatory, University of Arizona), Carlos S. Frenk (University of Durham), Simon D.M. White (MPI fur Astrophysik)

But what is $\rho_{DM}(r)$?

- **Cuspy:** NFW, Einasto, Moore
- **Cored:** Burkert, isothermal
- Profiles can agree near the Solar position but differ dramatically toward the **Galactic Center**

$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}(r(\ell, \theta)) d\ell$$



For annihilation searches toward the Galactic Center, the inner density profile can dominate the astrophysical uncertainty.

J-factors, D-factors, and density profiles

The astrophysical contribution to the flux depends entirely on the dark-matter distribution.

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}^2(r(\ell, \theta)) d\ell$$

[Submitted on 13 Nov 1996 (v1), last revised 21 Oct 1997 (this version, v4)]

A Universal Density Profile from Hierarchical Clustering

Julio F. Navarro (Steward Observatory, University of Arizona), Carlos S. Frenk (University of Durham), Simon D.M. White (MPI fur Astrophysik)

But what is $\rho_{DM}(r)$?

- **Cuspy:** NFW, Einasto, Moore
- **Cored:** Burkert, isothermal
- Profiles can agree near the Solar position but differ dramatically toward the **Galactic Center**

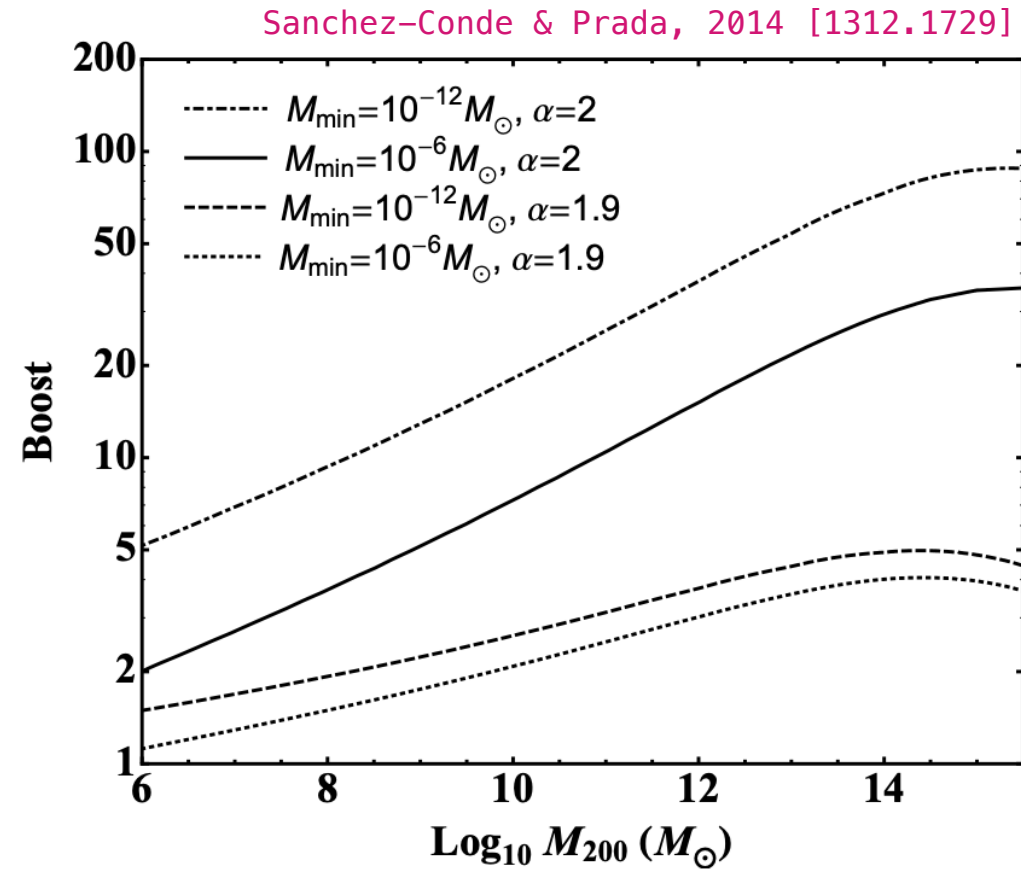
$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{DM}(r(\ell, \theta)) d\ell$$

Q3. To the best of my knowledge, the first mention of the term J-factor appears in [Bergstrom & Ullio 1997, [hep-ph/9706232](https://arxiv.org/abs/hep-ph/9706232)]. I never was able to trace back the origin of the name---are you?

For annihilation searches toward the Galactic Center, the inner density profile can dominate the astrophysical uncertainty.

Small-scale clumpiness: substructure boosts

- The annihilation signal depends on ρ_{DM}^2 , so it is sensitive to **clumpiness**
- Dense subhalos within a larger halo can increase the annihilation luminosity relative to a smooth distribution (**boost factor**)
- For annihilation, the boost factor can be non-negligible (for decay much less significant)
- Very difficult to characterize: the boost factor depends on poorly known properties of the small-scale halo population
- Also curious: dark matter spikes around black holes (albeit density profile modification, not substructure)



Dark Matter (DM) spikes

(cold, particle)

black hole

DM halo

Astrophysical Processes

*adiabatic growth of a black hole embedded
within a dark matter halo*

(see, e.g., Gondolo & Silk 1999)

High Density Fluctuations

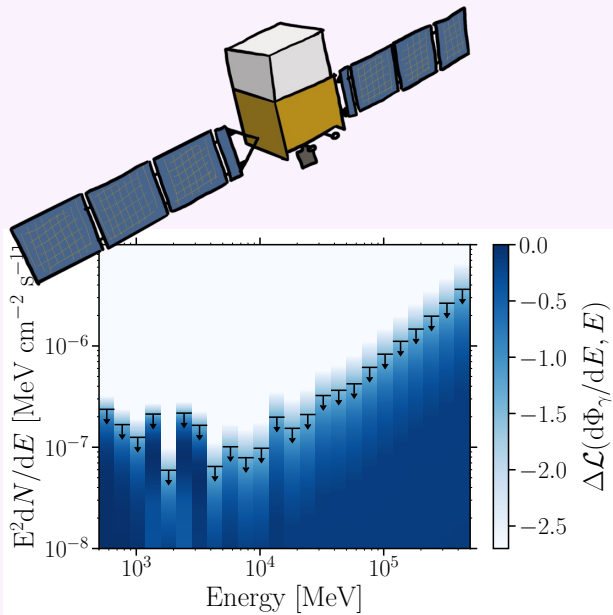
*such as (primordial) black holes formed in
the early Universe*

(see, e.g., Bertschinger 1985)

Dark Matter signal: what do we observe?

DM flux

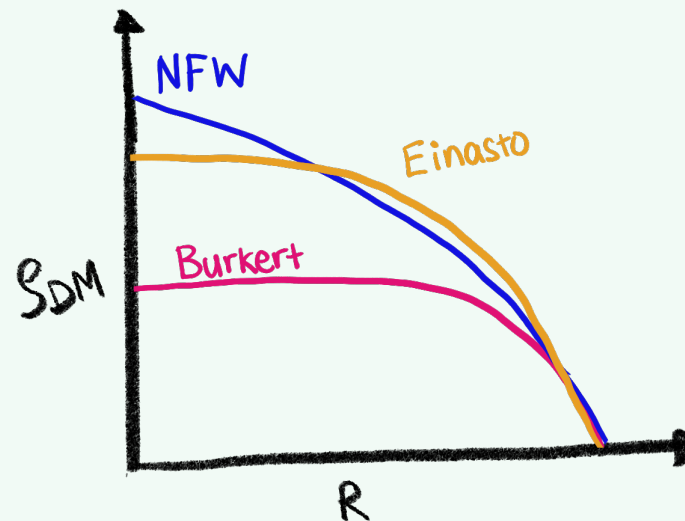
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

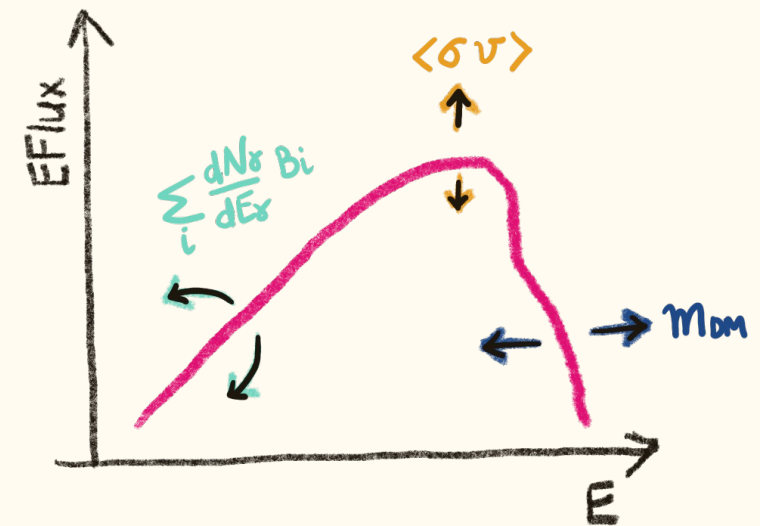
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

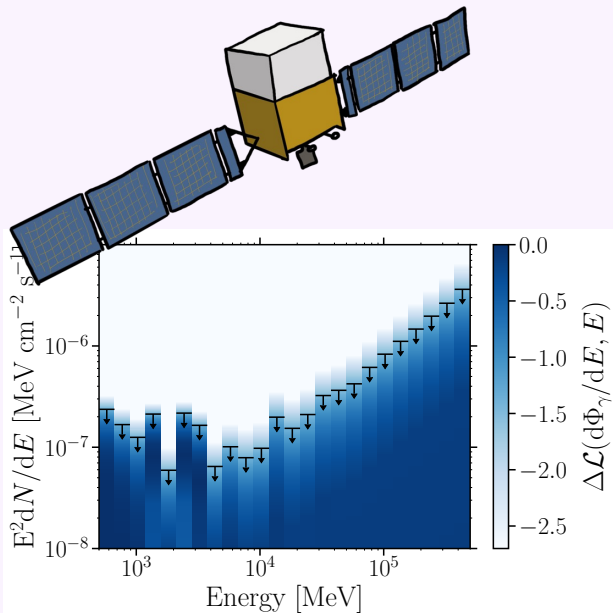
$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



Dark Matter signal: what do we observe?

DM flux

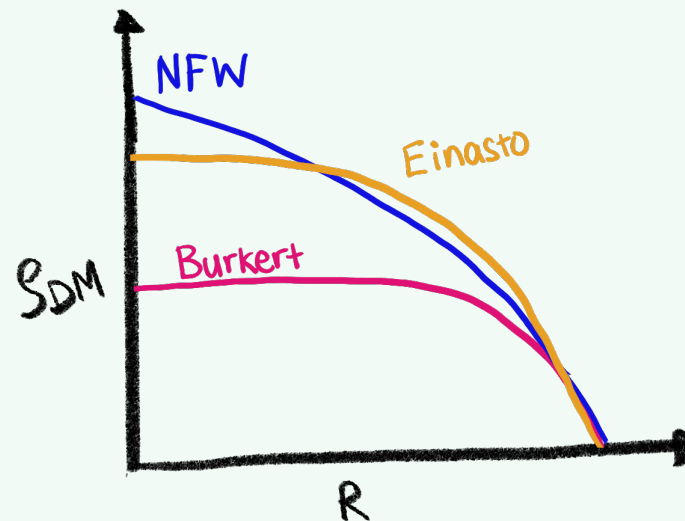
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

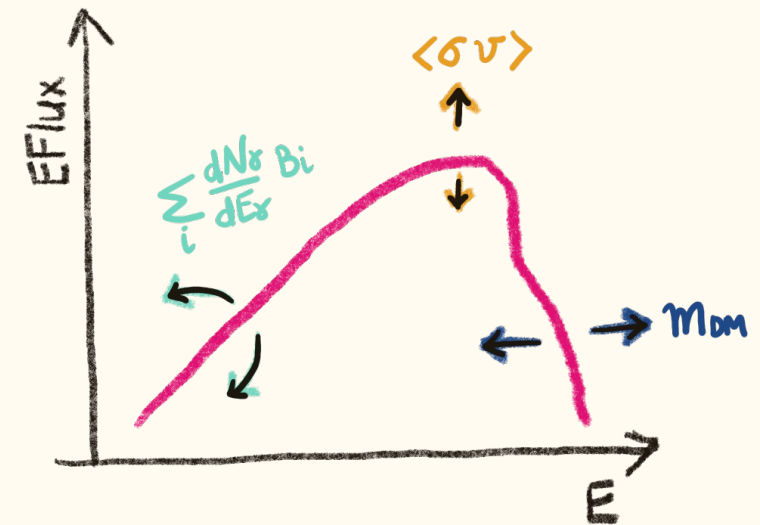
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



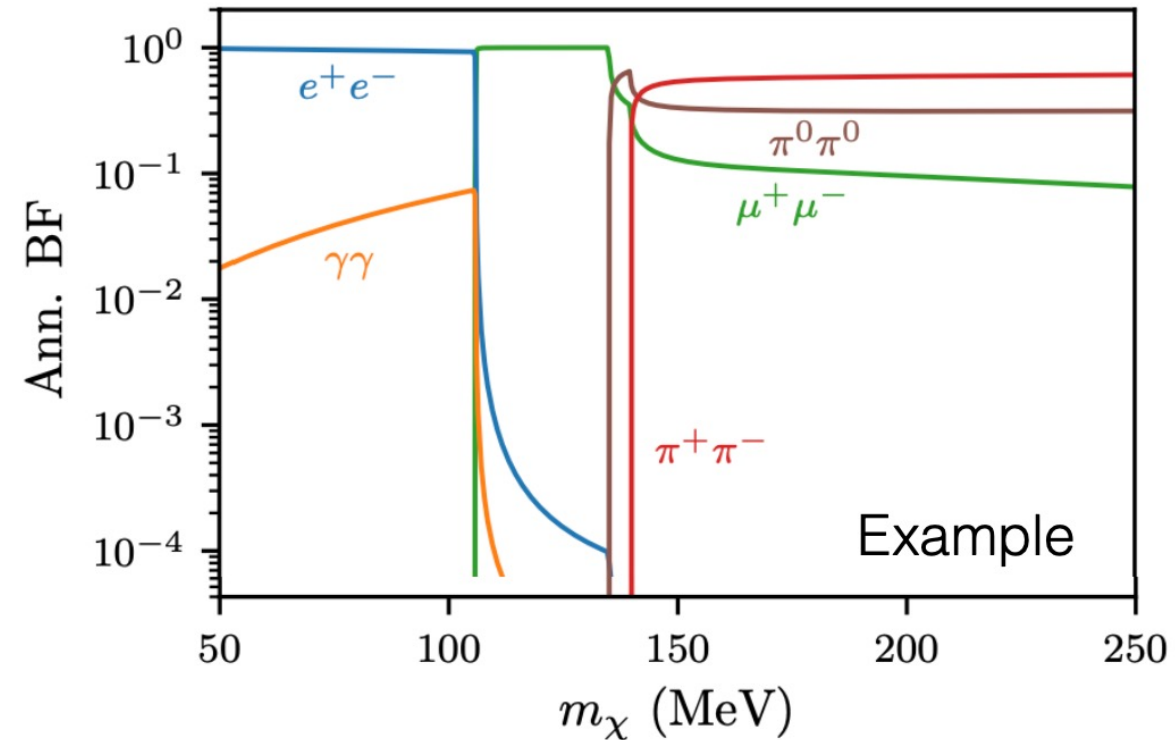
Primary annihilation spectra

- For a specific WIMP model, we can calculate the total number of x particles produced per annihilation as:

$$\frac{dN_x}{dE} = \sum_f B_f \frac{dN_{x,f}}{dE}$$

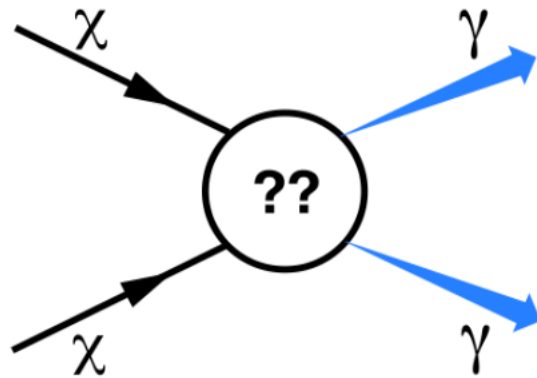
where B_f are the branching fractions into the various final states.

- These branching fractions depend on the couplings and interactions of the DM model, so to be as model-independent as possible, we often constrain a single **annihilation channel** at a time.



Gamma-ray lines

- Perhaps the simplest annihilation spectrum is for annihilation into two gamma rays (or neutrinos). This gives rise to a mono-chromatic photon flux. Each photon carries the rest mass energy of the DM:



$$\frac{dN_\gamma}{dE_\gamma} = 2\delta(E_\gamma - m_\chi)$$

- Considering DM in the mass range GeV-TeV, leads to a spectrum of gamma-rays.
- Gamma-ray lines are hard to produce in nature. This would be a 'smoking gun' signal of Dark Matter!
- Other annihilation channels still produce gamma rays, but with a less distinctive 'continuum' spectrum...
- Note:** The prompt flux from neutrinos follows in a similar way as for photons

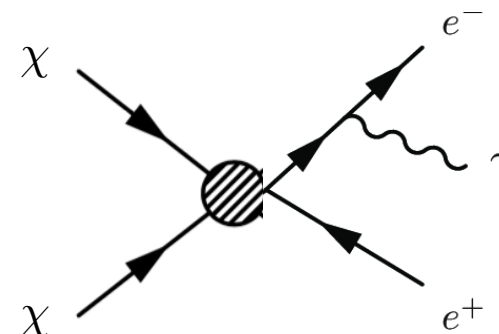
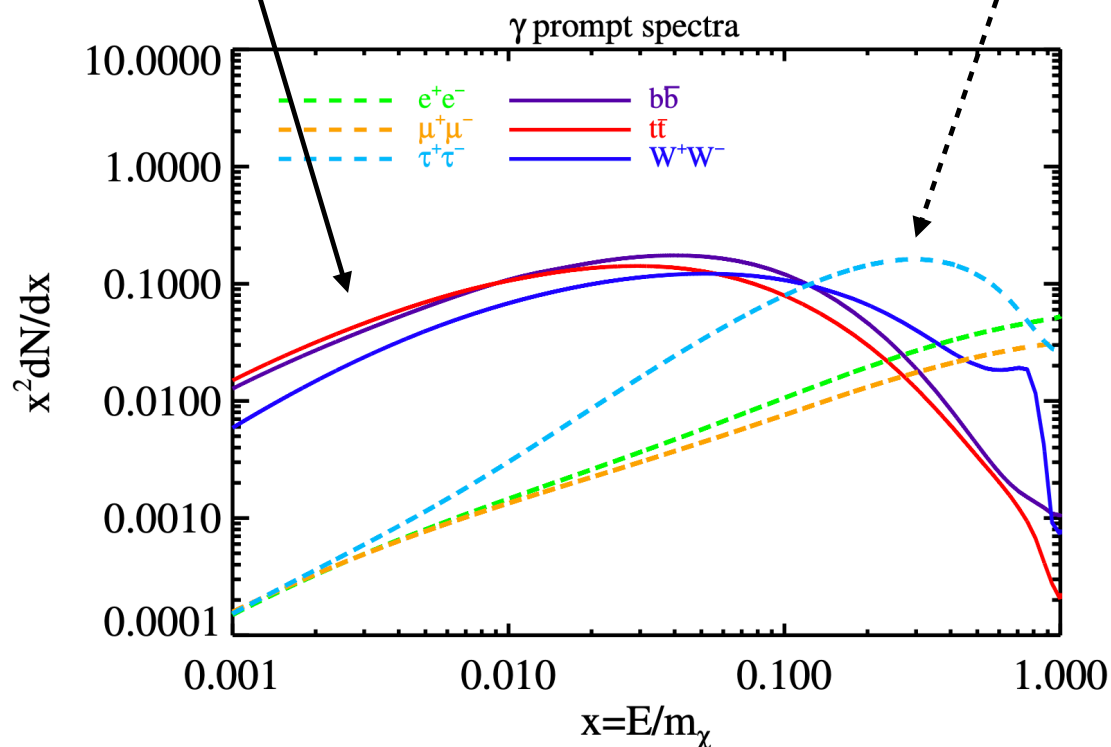
c. Bradley J Kavanagh

Gamma-ray spectra

Soft channels - hadronisation produces neutral pions which decay into photons

$$\pi^0 \rightarrow \gamma + \gamma$$

Hard channels - gamma rays from final state radiation

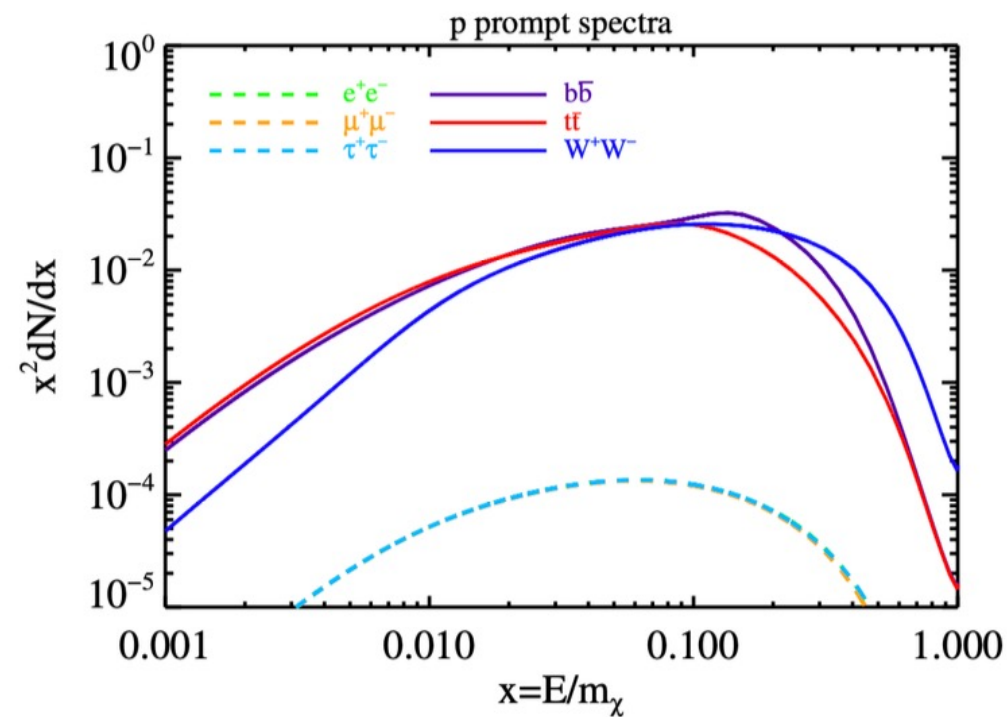
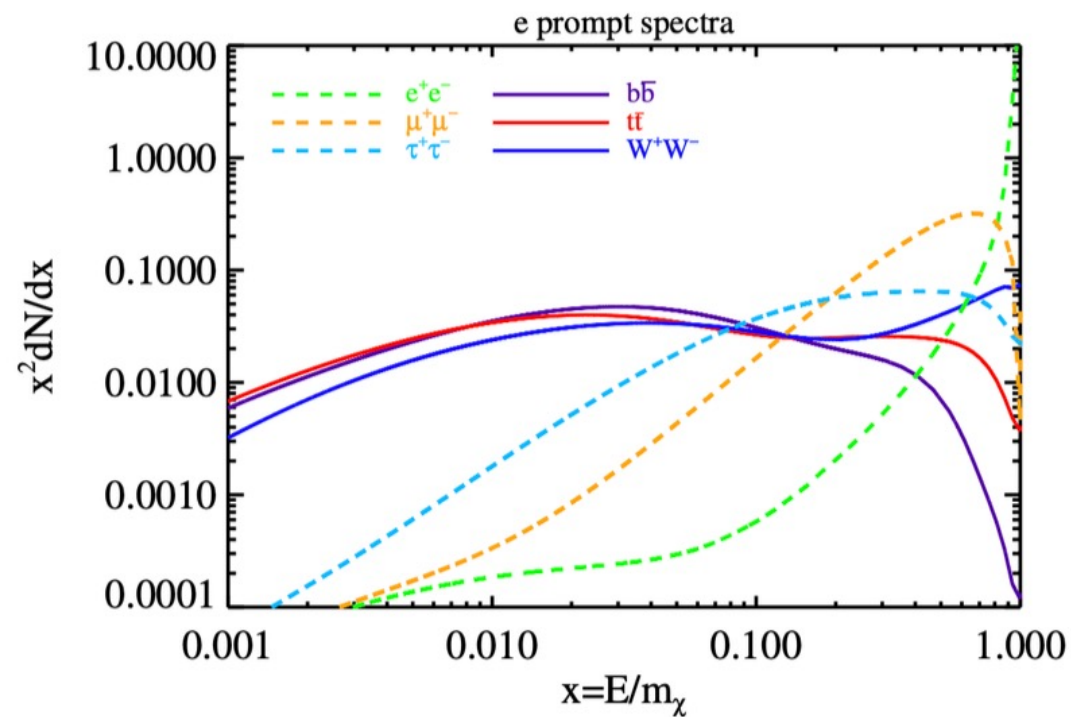


[Tools like [PPPC4DMID](#), [1012.4515](#); [Hazma](#), [1907.11846](#), [2207.07634](#)]

NB: Annihilation to light quarks can be more complicated, due to hadronic resonances.

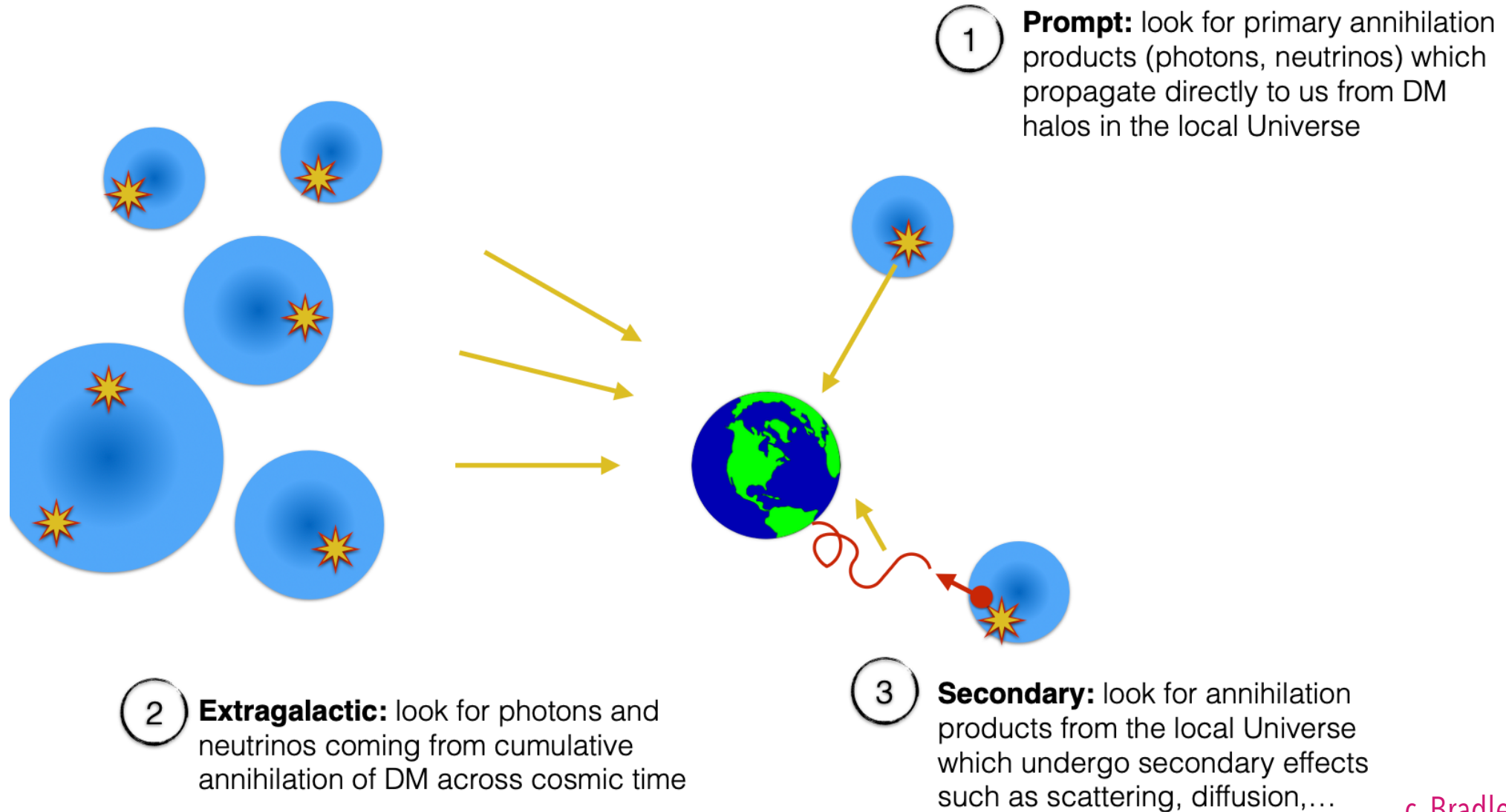
c. Bradley J Kavanagh

Charged particles



c. Bradley J Kavanagh

Types of annihilation signal



c. Bradley J Kavanagh

DM annihilation rates

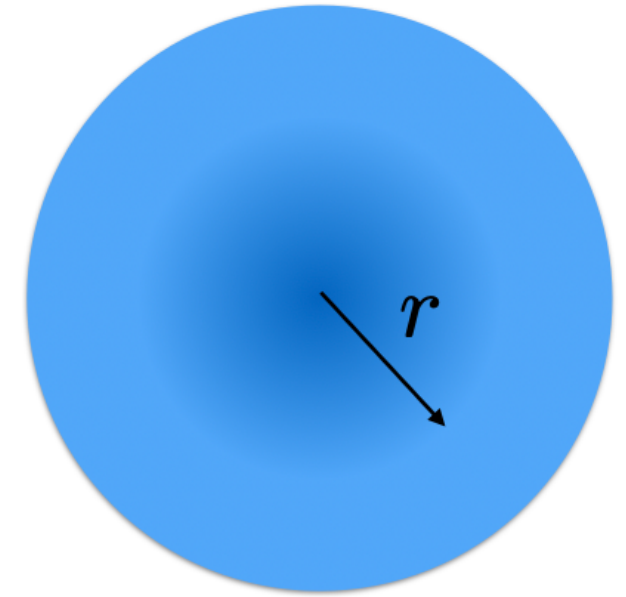
Rate of DM annihilation per unit time:*

$$\begin{aligned}\Gamma_{\text{ann}}(r, v) &= \Phi_{\chi} \times N_T \times \sigma \\ &= \frac{1}{2} n_{\chi} v \times n_{\chi} \times \sigma_{\text{ann}}(v) \\ &= \frac{1}{2} \frac{\rho_{\chi}(r)}{m_{\chi}} v \times \frac{\rho_{\chi}(r)}{m_{\chi}} \times \sigma_{\text{ann}}(v)\end{aligned}$$

Average over velocity distribution of DM particles:

$$\begin{aligned}\langle \Gamma_{\text{ann}}(r) \rangle &= \frac{1}{2} \left(\frac{\rho_{\chi}(r)}{m_{\chi}} \right)^2 \times \int \sigma_{\text{ann}}(v) v f(\mathbf{v}) d^3\mathbf{v} \\ &= \frac{1}{2} \left(\frac{\rho_{\chi}(r)}{m_{\chi}} \right)^2 \times \langle \sigma_{\text{ann}} v \rangle\end{aligned}$$

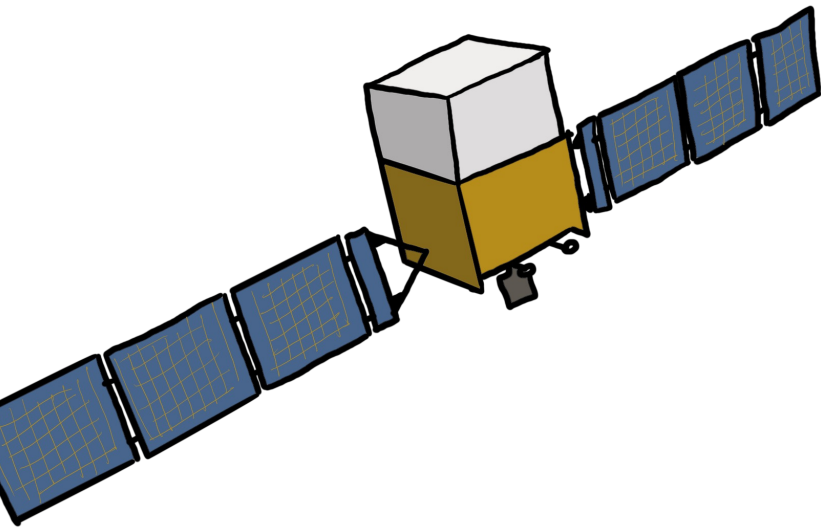
Typically, DM velocity dispersion is small, so only consider leading contribution σ_0 (“s-wave”) to annihilation cross section. “P-wave” $\propto (v/c)^2$ is typically suppressed.



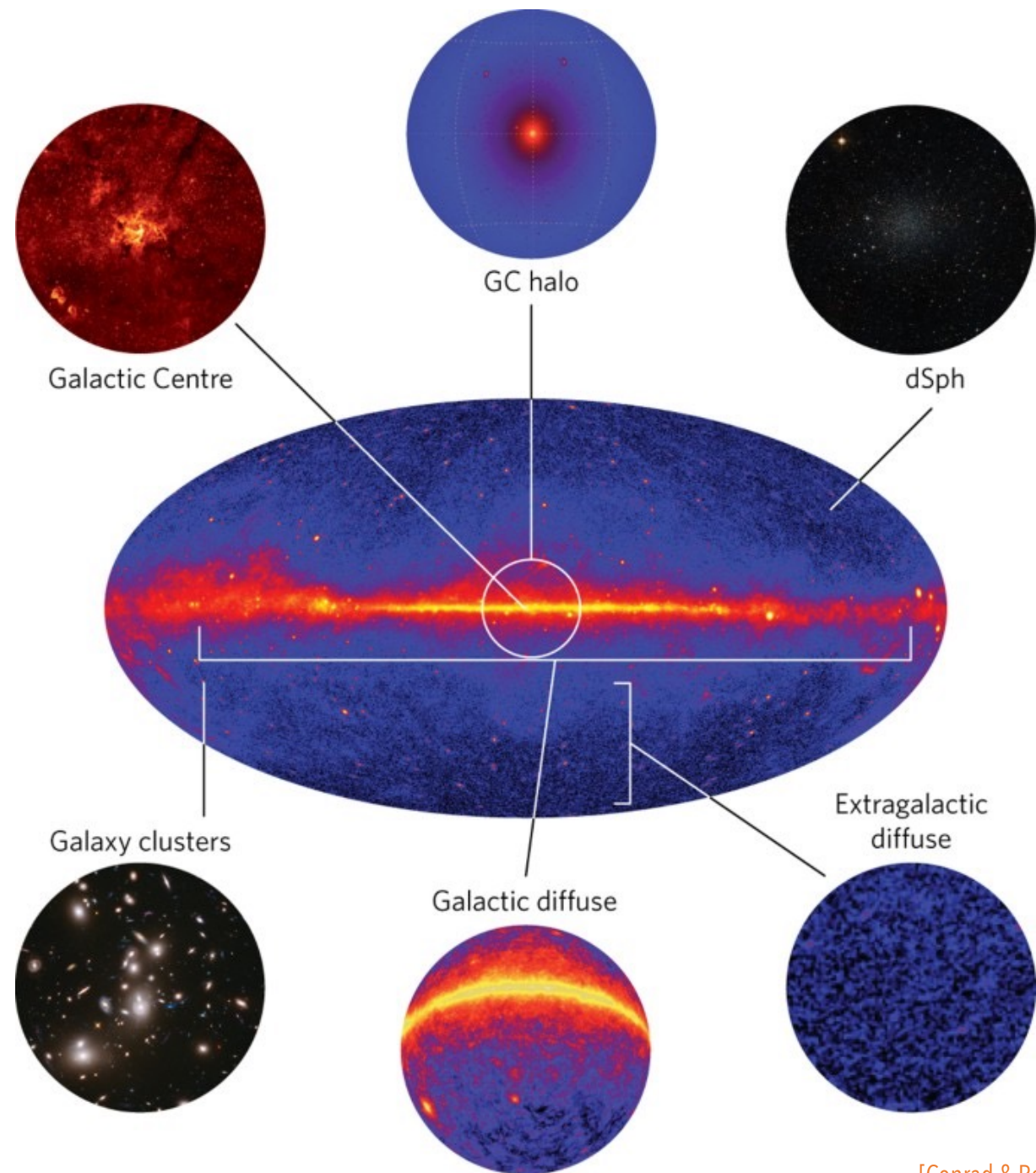
Typical velocity dispersion in Galactic halos and sub-halos:

$$\begin{aligned}\sigma_v &\sim 20 - 200 \text{ km/s}^2 \\ &\sim 10^{-4} - 10^{-3} c\end{aligned}$$

$$\sigma(v)v \approx \sigma_0 + \sigma_1(v/c)^2 + \dots$$

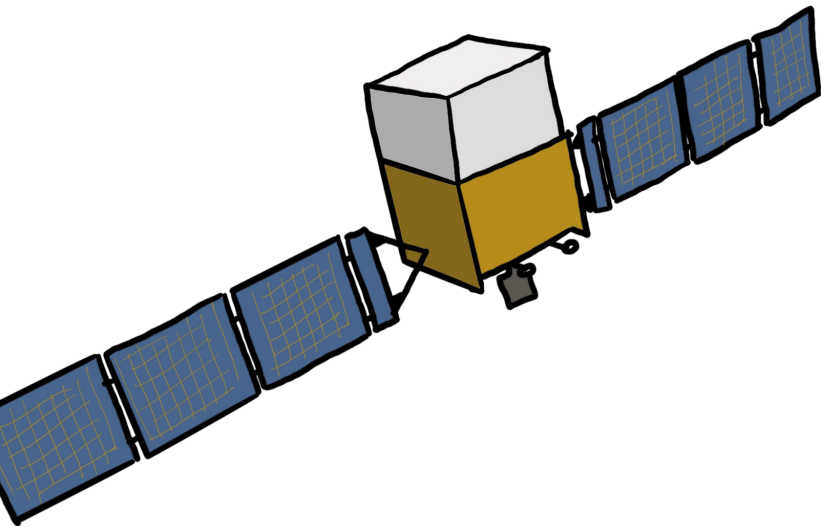


DM targets

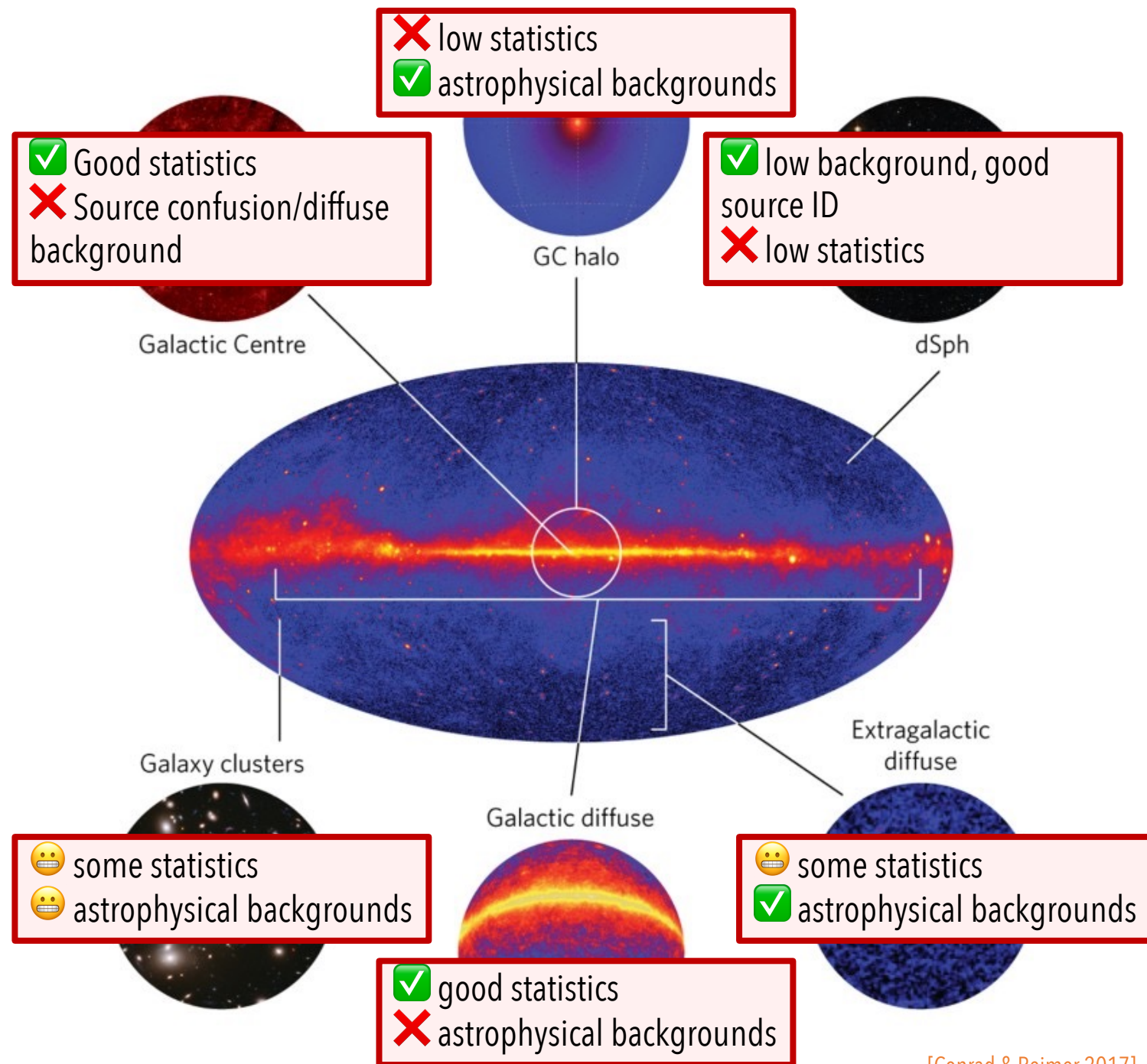


Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.

[Conrad & Reimer 2017]



DM targets

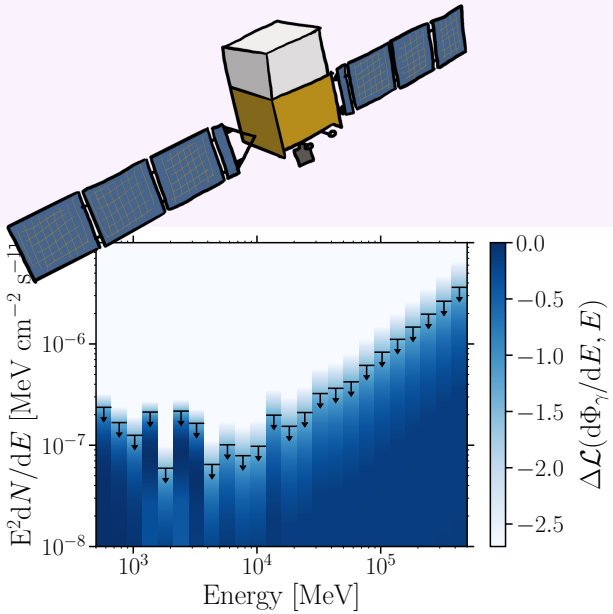


Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
 Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.

Take-home message

DM flux

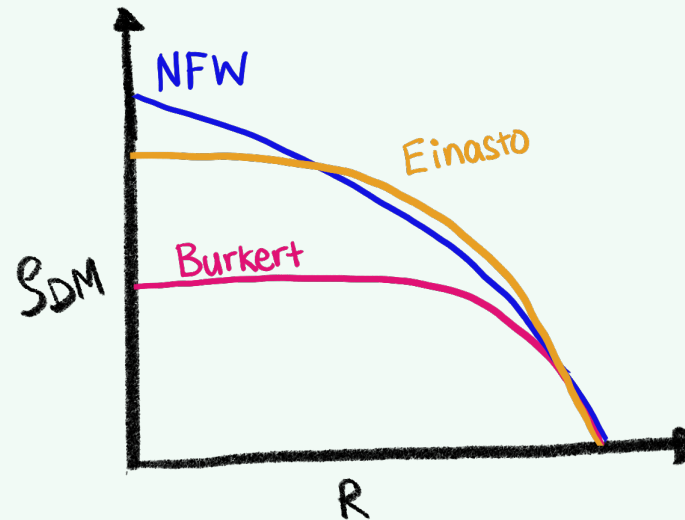
$$\frac{d\Phi}{dE}$$



=

**astrophysics
J-factor**

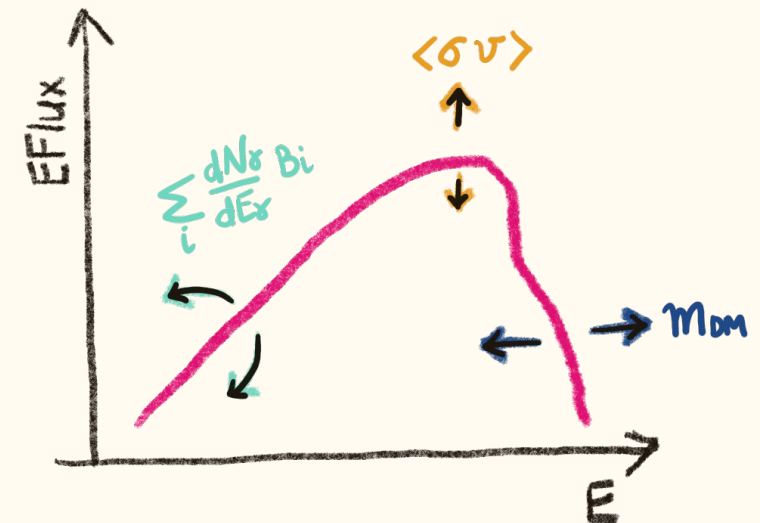
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



FERMILAB-PUB-09-494-A

**Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The
Fermi Gamma Ray Space Telescope**

Lisa Goodenough¹ and Dan Hooper^{2,3}

¹Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003

²Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510

³Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

FERMILAB-PUB-09-494-A

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Goodenough¹ and Dan Hooper^{2,3}

Department of Physics, New York University, New York, NY 10003
National Accelerator Laboratory, Batavia, IL 60510
University of Chicago, Chicago, IL 60637

OBSERVATIONS OF M31 AND M33 WITH THE FERMILARGE AREA TELESCOPE: A GALACTIC CENTER EXCESS IN ANDROMEDA?

V. ACKERMANN¹, M. AJELLO², A. ALBERT³, L. BALDINI⁴, J. BALET⁵, G. BARBIELLINI^{6,7}, D. BASTIERI^{8,9}, R. BELLAZZINI¹⁰,
E. BISSALDI¹¹, E. D. BLOOM¹², R. BONINO^{13,14}, E. BOTTACINI¹², T. J. BRANDT¹⁵, J. BREGEON¹⁶, P. BRUEL¹⁷,
R. BUEHLER¹, R. A. CAMERON¹², R. CAPUTO¹⁸, M. CARAGIULO^{11,19}, P. A. CARAVEO²⁰, E. CAVAZZUTI²¹, C. CECCHI^{22,23},
E. CHARLES¹², A. CHEKHTMAN^{24,61}, G. CHIARO⁹, S. CIPRINI^{21,22}, P. A. COSTANZA¹¹, S. CUTINI^{21,22}, F. D'AMMANDO^{25,26},
F. DE PALMA^{11,27}, R. DESIANTE^{13,28}, S. W. DIGEL¹², N. DI LALLA⁴, F. GIORDANO^{11,19}, S. GIROLETTI²⁵, T. GLANZMAN¹²,
S. FUNK²⁹, P. FUSCO^{11,19}, F. GARGANO¹¹, N. GIGLIETTO^{11,19}, F. GUARIECI^{15,62}, K. HAYASHI³³, M. DI MAURO¹², L. DI VENERE^{11,19},
D. GREEN^{15,30}, I. A. GRENIER⁵, L. GUILLEMOT^{31,32}, S. KUSS¹⁰, G. LA MURA⁹, S. LARSSON^{42,43}, L. LATRONICO¹³, J. LI⁴⁴,
T. KAMAE³⁹, J. KNÖDLSER^{40,41}, A. K. H. KONG³⁵, S. MALDERA¹³, W. MITTHUMSIRI⁴⁵, A. MANFREDI⁴, P. MARTIN^{40,41},
F. LONGO^{6,7}, F. LOPARCO^{11,19}, P. LUBRANO²², S. MIRABAL^{15,62}, D. MALYSHEV²⁹, T. OHMURA⁴⁶, T. MIZUNO⁴⁶, M. E. MONZANI¹²,
M. N. MAZZIOTTA¹¹, P. F. MICHELSON¹², N. NEGRO^{13,14}, E. NUSS¹⁶, T. OHSUGI⁴⁶, N. OMODEI¹², E. ORLANDO¹²,
A. MORSELLI⁴⁷, I. V. MOSKALENKO¹², M. PERSIC^{6,50}, M. PESCE-ROLLINS¹⁰, F. PIRON¹⁶, T. A. PORTER¹², G. PRINCIPE²⁹,
J. F. ORMES⁴⁸, D. PANEQUE⁴⁹, M. RAZZANO^{10,63}, O. REIMER^{12,51}, M. SÁNCHEZ-CONDE^{43,52}, C. SGRÒ¹⁰, D. SIMONE¹¹,
S. RAINÒ^{11,19}, R. RANDO^{8,9}, F. SPADA¹⁰, G. SPANDRE¹⁰, P. SPINELLI^{11,19}, K. TANAKA⁵⁴, L. TIBALDO⁵⁵, D. F. TORRES^{44,56},
E. J. SISKIND⁵³, Y. UCHIYAMA⁵⁷, J. C. WANG^{34,36,37}, K. S. WOOD^{58,61}, M. WOOD¹², G. ZAHARIJAS^{59,60}, M. ZHOU^{34,36,37}

Draft version March 1, 2017

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The
Fermi Gamma Ray Space Telescope

Goodenough¹ and Dan Hooper^{2,3}
¹Department of Physics, New York University, New York, NY 10003
²National Accelerator Laboratory, Batavia, IL 60510
³University of Chicago, Chicago, IL 60637

Department of Physics, University of Chicago, Chicago, IL 60637

OBSERVATIONS OF M31 AND M33 WITH THE FERMI LARGE AREA TELESCOPE:
A GALACTIC CENTER EXCESS IN ANDROMEDA?

NN¹, M. AJELLO², A. ALBERT³, L. BALDINI⁴, J. BALLEST⁵, G. BARBIELLINI^{6,7},
ALDI¹¹, E. D. BLOOM¹², R. BONINO^{13,14}, M. E. BOTTACINI¹²,
R. A. CAMERON¹², R. CAPUTO¹⁸, G. CHIARO⁹, S. CARAGIULO^{11,19}, T. J. P.
A. CHEKHTMAN^{24,61}, F. FUSCO^{11,19}, S. W. DIGET¹², S. CIPRIANO¹⁵,
R. DESIANTE^{13,28}, S. NÖRDBLAD¹⁶, F. GARGAN¹⁷, T. A. GREIF⁵

1
OBSERVATIONS OF M31 AND M33 WITH THE FERMI LARGE AREA TELESCOPE:
A GALACTIC CENTER EXCESS IN ANDROMEDA?
V. ACKERMANN¹, M. AJELLO², A. ALBERT³, L. BALDINI⁴, J. BALLEST⁵, G. BARBIELLINI^{6,7}, D. BASTIERI^{8,9},
E. BISSALDI¹¹, E. D. BLOOM¹², R. BONINO^{13,14}, E. BOTTACINI¹², T. J. BRANDT¹⁵, J. BREGESCO¹¹,
R. BUEHLER¹, R. A. CAMERON¹², R. CAPUTO¹⁸, M. CARAGIULO^{11,19}, P. A. CARAVEO²⁰,
E. CHARLES¹², R. CHEKHTMAN^{24,61}, G. CHIARO⁹, S. CIPRINI^{21,22}, F. COSTANZI¹¹,
F. DE PALMA^{11,27}, A. DESIANTE^{13,28}, S. W. DIGEL¹², N. DI LALLA⁴,
S. FUNK²⁹, P. FUSCO^{11,19}, F. GARGANO¹¹, N. GIGLIETTO^{11,19},
D. GREEN^{15,30}, I. A. GRENIER⁵, L. GUILLEMOT^{31,32},
G. KAMAE³⁹, J. KNÖDLSER^{40,41},
F. LONGO^{6,7}, F. LOPARCO^{11,19},
M. N. MAZZIOTTA⁴,
A. MORSE¹

Fermi-LAT Observations of γ -Ray Emission toward the Outer Halo of M31

Christopher M. Karwin¹ , Simona Murgia¹ , Sheldon Campbell¹, and Igor V. Moskalenko²

¹ Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; ckarwin@uci.edu, smurgia@uci.edu

² Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
imos@stanford.edu

Received 2019 March 19; revised 2019 June 7; accepted 2019 June 8; published 2019 July 30

On The Gamma-Ray Emission From Reticulum II and Other Dwarf Galaxies

Dan Hooper^{1,2} and Tim Linden³

¹Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL

²University of Chicago, Department of Astronomy and Astrophysics Chicago, IL

³Kavli Institute for Cosmological Physics University of Chicago Chicago, IL

Possible Evidence For Dark Matter
Fermi Gamma

OBSERVATIONS OF M31 AND M33 WITH THE FERMI LARGE AREA TELESCOPE:
A GALACTIC CENTER EXCESS IN ANDROMEDA?

V. ACKERMANN¹, M. AJELLO², A. ALBERT³, L. BALDINI⁴, J. BALET⁵, G. BARBIELLINI^{6,7}, D. BASTIERI^{8,9},
E. BISSALDI¹¹, E. D. BLOOM¹², R. BONINO^{13,14}, E. BOTTACINI¹², T. J. BRANDT¹⁵,
R. BUEHLER¹, R. A. CAMERON¹², R. CAPUTO¹⁸, M. CARAGIULO^{11,19}, P. A. CARAVEO²⁰, J. BREGEON¹⁶,
E. CHARLES¹², A. CHEKHTMAN^{24,61}, G. CHIARO⁹, S. CIPRINI^{21,22}, P. A. CARAVEO²⁰, J. BREGEON¹⁶,
F. DE PALMA^{11,27}, R. DESIANTE^{13,28}, S. W. DIGEL¹², N. DI LALLA⁴, M. COSTANZI¹¹,
S. FUNK²⁹, P. FUSCO^{11,19}, F. GARGANO¹¹, L. GUILLEMOT^{31,32},
D. GREEN^{15,30}, I. A. GRENIER⁵, A. K. H. B. DE OLIVEIRA³³,
T. KAMAE³⁹, J. KNÖDLSER^{40,41},
F. LONGO^{6,7}, F. LOPARCO^{11,19},
M. N. MAZZIOTTA¹¹,
A. MORSE¹¹

CrossM

Fermi-LAT Observations of γ -Ray Emission toward the Outer Halo of M31

Christopher M. Karwin¹ , Simona Murgia¹ , Sheldon Campbell¹, and Igor V. Moskalenko² 

¹Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA; ckarwin@uci.edu, smurgia@uci.edu

²Hansen Experimental Physics Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
imos@stanford.edu

Received 2019 March 19; revised 2019 June 7; accepted 2019 June 8; published 2019 July 30

SAHARIJAS^{59,60}, D. F. TORRES^{44,56},
SIMONE¹¹,
M. ZHOU^{34,36,37}

Possible Evidence For Dark Matter
Fermi Gamma-ray

Gamma-Ray Emission From Reticulum II and Other Dwarf Galaxies

Legacy Analysis of Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with 14 Years of *Fermi*-LAT Data

OBSERVATIONS OF M31 AND
A GALACTIC
V. ACKERMANN¹, M. AJELLO², A. ALBERT³, L.
E. BISSALDI¹¹, E. D. BLOOM¹², R. BONIN
R. BUEHLER¹, R. A. CAMERON¹², R. CAPUTO
E. CHARLES¹², A. CHEKHTMAN^{24,61}, G. CHIA
F. DE PALMA^{11,27}, R. DESIANTE^{13,28}, S. W. DIC
S. FUNK²⁹, P. FUSCO^{11,19}, F. GARGANO¹¹, N
D. GREEN^{15,30}, I. A. GRENIER⁵, L. GUILLEMOT
T. KAMAE³⁹, J. KNÖDLSER^{40,41}, A. K. H
F. LONGO^{6,7}, F. LOPARCO^{11,19}, A. K. H
A. MORSE

Alex McDaniel* and Marco Ajello
Department of Physics and Astronomy, Clemson University, Clemson, SC, 29631, USA

Christopher M. Karwin
NASA Postdoctoral Program Fellow, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA

Mattia Di Mauro
Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy and
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

Alex Drlica-Wagner
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA and
Department of Astronomy and Astrophysics, University of Chicago, Chicago IL 60637, USA

Miguel Sánchez-Conde
Instituto de Física Teórica, IFT UAM-CSIC, Departamento de Física Teórica,
Universidad Autónoma de Madrid, ES-28049 Madrid, Spain
(Dated: November 10, 2023)

Fermi-LAT Observations of

Christopher M. Karwin¹ , Simo

¹ Department of Physics and Astronomy, Un

² Hansen Experimental Physics Laboratory and Kavli In

Received 2019 March 19;

Possible Evidence For Dark Matter Fermi Gamma-ray

Gamma-Ray Emission From Reticulum II and Other Dwarf Galaxies

Legacy Analysis of Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with 14 Years of *Fermi*-LAT Data

OBSERVATIONS OF M31 AND
A GALACTIC

V. ACKERMANN¹, M. AJELLO², A. ALBERT³, L.
E. BISSALDI¹¹, E. D. BLOOM¹², R. BONIN
R. BUEHLER¹, R. A. CAMERON¹², R. CAPUTO
E. CHARLES¹², A. CHEKHTMAN^{24,61}, G. CHIA
F. DE PALMA^{11,27}, R. DESIANTE^{13,28}, S. W. DIC
S. FUNK²⁹, P. FUSCO^{11,19}, F. GARGANO¹¹, N
D. GREEN^{15,30}, I. A. GRENIER⁵, L. GUILLEMOT
T. KAMAE³⁹, J. KNÖDLSER^{40,41}, A. K. H
F. LONGO^{6,7}, F. LOPARCO^{11,19}, A. K. H
A. MORSE

Alex McDaniel* and Marco Ajello
Department of Physics and Astronomy, Clemson University, Clemson, SC, 29631, USA

Christopher M. Karwin
NASA Postdoctoral Program Fellow, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA

Mattia Di Mauro
Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy and
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

Alex Drlica-Wagner
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA and
Department of Astronomy and Astrophysics, University of Chicago, Chicago IL 60637, USA

Miguel Sánchez-Conde
Instituto de Física Teórica, IFT UAM-CSIC, Departamento de Física Teórica,
Universidad Autónoma de Madrid, ES-28049 Madrid, Spain
(Dated: November 10, 2023)

Fermi-LAT Observations of

Christopher M. Karwin¹ , Simo
¹ Department of Physics and Astronomy, Un
² Hansen Experimental Physics Laboratory and Kavli In

Received 2019 March 19;



some reports of excesses in the MW halo
and galaxy clusters (line and extended...)